Stage Acoustics in Concert Halls:

a study of musicians' acoustical environment

Master of Science Thesis in the Master's Programme Sound and Vibration

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Designing concert hall acoustics is a prestigious task which demands high accuracy of acoustical measures such as support, strength, reverberation, and other numerous parameters. However, little is known about the acoustical environment on stages in concert halls and how the design of environments are perceived by musicians. Therefore, Norconsult/Akustikon supported an investigation of measures that can be used by acousticians in the design process to evaluate the quality of sound environments on concert hall stages.

The method for evaluating the acoustical environment was through measurements and calculations of several stages. Four concert halls in Sweden were measured in the following cities: Gävle, Jönköping, Västerås, and the current hall in Malmö. Out of these four halls, calculations of Gävle, Jönköping, and Västerås were performed. However, the new hall in Malmö was used instead of the old concert hall. In addition to these calculations, Musikverein in Vienna was calculated to compare the data to a concert hall which is famous for its acoustical qualities. Through surveys, the opinions of the musicians concerning their home stages were gathered in four concert halls with a total of 102 participants. Statistical tools such as arithmetic mean, median, standard deviation, and Spearman's ranking coefficient were some of the tools used to evaluate and compare the collected data.

This master's thesis investigates the acoustical environment on concert hall stages and correlation between subjective opinions of musicians and objective measured and calculated parameters. The purpose is to explore the tools used by acousticians in architectural acoustics and understand the effect that various design choices have on the opinion of the users. Furthermore, correlation between calculations and measurements was studied in order to understand relevance of tools used by acousticians. A literature study of concert hall acoustics was implemented concerning both physical aspects of sound as well as measures currently used to evaluate the acoustical qualities of spaces for music. In addition, previous research and common rules for stage design were presented along with descriptions of some of the top ranked concert halls and halls included in this study. Basic statistics was also presented to explain the calculations used in this master's thesis and the relevance of collected data.

As for the results, the hearing self [HS] category in the survey has similar opinions among most of the participants, except for outliers. In Malmö, the opinion of HS varies more than the three other halls. In the dynamics [DYN] category of the survey in Malmö, significant differences between different instrument groups are found. Nonetheless, further investigations with more concert halls are needed to establish any correlation. A higher ranked hall is more likely to have a neutral colored sound in contrast to dark or sharp. Halls with a lower rank tend to yield more responses of sharp coloration. Yet, it can always be discussed whether a neutral sound is optimal or if coloration of the sound may actually contribute to further depth of the sound in the hall.

As for the difference between measurements and calculations, late support values are similar between calculation and measurement. In contrast, early support differs between calculation and measurement which may be explained by the lack of absorption in the measurement and lack of detail in the CATT-Acoustics model used for computer calculations. Lateral fraction [LF] has yielded unpredictable results for the measurements and the reason for this is unknown. High measurements of LF were found in both Gävle and Malmö. CATT-Acoustic tends to overestimate measures such as clarity, definition, and treble ratio. In contrast, early decay time and early support tend to have lower calculated values as opposed to measured.

No significant monotonic relation between the measures for architectural acoustics and subjective opinions of musician in concert halls have been found. However, in the individual halls there are moderate to high correlations suggesting that there may be certain monotonic relations which are strictly individual to the concert hall in question.

Keywords: stage acoustics, concert halls, symphony orchestra, correlation, survey, musicians, measurements, calculation, opinions, support, musical acoustics, architectural acoustics

Contents

Preface

In the spring of 2013, Emelie Olofsson concluded her thesis at Akustikon/Norconsult which will act as a basis for further investigation of correlation between objectively measured parameters and subjective impressions. Emilie's thesis covers calculations using CATT-Acoustic in three different concert halls, but lacks measurement data and correlation between parameters and surveys. Due to changes in positions on stage, which are motivated in the method section, calculations are executed for other positions.

This master thesis is aimed at complementing Emilie's work with measurements and opinions of the musicians in five different concert halls. With this data it is then possible to statistically evaluate if there is any correlation between subjective and objective collected data. The hypothesis of this thesis is stated as, objective measures used by acousticians to evaluate acoustical conditions on stages should correlate to the opinions of musicians in order to provide useful tool when designing concert hall stages.

Acknowledgements

The support from team members at Akustikon/Norconsult has been greatly appreciated throughout the process of this master thesis. Special thanks to Jan-Inge Gustafsson who has supervised the thesis and shared his vast knowledge of stage acoustics. Furthermore, Jan-Inge has assisted in measurements in Jönköping and Malmö making the measurements possible within the time frame of the concert halls staff. Another member at Akustikon/Norconsult which deserves an honorable mention is Mats Olsson who has educated me in measurement techniques and answered many concerns and questions. Emelie Olofsson has made an interesting study which has been the foundation for the continuation of this master thesis. Anders Gade, Jens Jørgen Dammerud, and Leo Beranek have performed research about stage acoustics which have inspired some of the investigations and methods used. Erkin Asutay at Chalmers has helped with guidance in statistical analysis and confirmed methods and approches to analysing the collected data. Symphonic orchestras in Gävle, Jönköping, Malmö, and Västerås have aided in answering surveys making the thesis work possible. Eric Wikström has helped with measurements in Gävle and Västerås and given support throughout this work.

Nomenclature

The lists below feature a collection of abbreviations used in this master thesis study sorted by Roman upper case letters, Roman lower case letters, and Greek lower case letters.

Roman upper case letters

AM	Amsterdam, Concertgebouw
Ba	Bassoon
BO	Boston, Symphony Hall
BR	Bass Ratio
C	Clarity
Cel	Cello
Cl	Clarinet
COL	Tone coloration
D	Definition
Db	Double Bass
DYN	Hall's dynamics
EDT	Early Decay Time
EEL	Early Ensemble Level
ENS	Feeling of ensemble
Fl	Flute
G	Strength or Gain
Hrn	Horn
HS	Ability to hear oneself
ISO	International Organization for Standardization
IQR	Interquartile range
$ITDG$	Initial-Time-Delay Gap
JND	Just Noticeable Difference
MTF	Modulation Transfer Function
N/A	Not Applicable or Not Available
Ob	Oboe
OAI	Overall Acoustic Impression
Perc	Percussion
REV	Reverberation
RT	Reverberation Time
RTC	Randomized-Tail-corrected Cone-tracing
SPL	Sound Pressure Level
SU	Sketch-Up
SubPar	Subjective parameters
SUP	Room's support
ST	Support
T	Reverberation Time
Trb	Trombone or Tuba
Trp	Trumpet
VBA	Visual Basic for Applications
Vla	Viola
Vl	Violin
VM	Vienna, Grosser Musikvereinsaal
Q	Quartile

Roman lower case letters

dB	Decibels
h	Height
l	Length
ms	Milliseconds
r	Correlation coefficient
rec	Receiver
s	Seconds
src	Source
w	Width

Greek lower case letters

ρ	Spearman's correlation coefficient

1 Introduction

1.1 Background

In the spring of 2013, Emelie Olofsson concluded her thesis at Akustikon/Norconsult which will act as a basis for further investigation of correlation between objectively measured parameters and subjective impressions. Olofsson's thesis covers calculations using CATT-Acoustic in three different concert halls, but lacks measurement data and correlation between parameters and surveys. Indeed, previous research concerning the correlation between subjective opinions and objective acoustical measurements in stage acoustics have not been able to find any significant correlation during the past 30 years.

1.2 Purpose

The purpose of this essay is to identify acoustic parameters that can be used in the design process to identify musicians' acoustical environment on stage. It is common that emphasis is put on achieving well-balanced acoustical qualities in the audience area, but there is less knowledge about what acoustical qualities are considered favorable by musicians.

In order to achieve the stated purpose, objective measurements of several concert halls are compared to the musicians' subjective judgment of the acoustical environment. Subjective judgment is collected through surveys and processed in Excel. In addition, computer simulations using CATT-Acoustic are compared to both measurement data and surveys in order to confirm possible correlations between measurements, calculations, and subjective opinions. Statistical tools such as standard deviations, mean values, medians, and Spearman's ranking coefficients are used to confirm validity of collected data and find possible correlations.

1.3 Limitations

This master thesis is limited to case studies of six different concert halls which Akustikon/Norconsult have worked with. These are Gävle's concert hall, Jönköping's SPIRA, Malmö's old concert hall, Malmö's new concert hall KKH, and Västerås' concert hall, and Musikverein in Vienna. In Gävle, Jönköping, and Västerås both measurements and calculations have been performed. However, Malmö's old concert hall only has measurements due to lack of a computer model. The new hall in Malmö is limited to only calculations due to that the construction of the hall is not complete. Musikverein in Vienna only has calculations due to its geographical proximity from Sweden and financial limitations.

Limitations are partly due to that the survey has already been designed and therefore there is no possibility to make any changes. Furthermore, only seven positions on the stage are investigated due to lack of time for measurement a processing of collected data. In turn, these seven positions are to define the total impression of various instrument groups, even though there might be considerable differences within the same instrument group. Finally, acoustic parameters which are to be measured are decided during the literature study and this limits the amount of data and what will be included in the final analysis.

Measurements are made with an omni-directional source, but in reality instruments have different directivity at different frequencies. This assumptions creates challenges in comparing sound paths between different instrument groups. Furthermore, this master thesis study does not include correlation of objective geometrical parameters which have been shown by Dammerud to have correlation to subjective opinions of musicians.

2 Theory

The theory section is based on a literature study made in the first five weeks of this study. This section examines theoretical knowledge of sound as well as research in the field of stage acoustics. Moreover, it acts as a foundation for further investigation of what types of acoustical parameters are suitable in order to measure the acoustical environment for musicians.

2.1 Properties of sound

2.1.1 Reverberation

In Figure 2.1, an emphasized version of a reflectogram is shown in order to illustrate the pattern of decaying sound in four different time regions. Time is the independent variable on the x-axis and it is often measured in milliseconds [ms] due to the path lengths in our architectural spaces. If two points are located 3.4 m apart and sound travels through air at about 340 meters per second, this would yield a travelling time of 10 ms. In turn, ms is more an appropriate measurement of time because it relates to dimensions in our built surroundings.

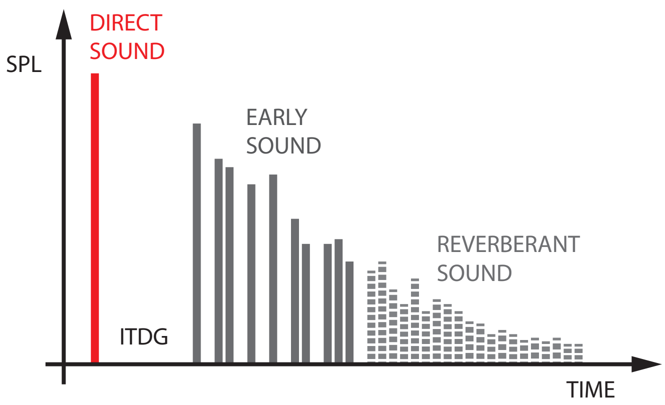

Figure 2.1: Exaggerated version of a reflectogram displaying the direct sound, ITDG, early sound, and reverberant sound.

The direct sound is defined as the sound energy which arrives at the receiver position between 0 to 10 ms and is the direct sound transmission between the source and receiver. Early sound is defined as the amount of sound energy which arrives up to 80 ms and generally has a lower temporal density than reverberant sound. Moreover, the early sound delays are caused by differences in the path of reflections and a lower SPL could be caused by the absorptive capabilities of the reflective surfaces. The reverberant sound is sound which arrives later than 80 ms and the reflection pattern is denser due to that the reflections have been distributed throughout the room (Beranek, 2004, p. 23). reflectograms are important tools used by acousticians in order to determine reflections which could be disruptive or need to be enhanced. Initial-time-delay gap [ITDG] is displayed in Figure 2.1 and is the time in milliseconds between the direct sound and the first early reflections (Beranek, 2004, p. 22).

In his report *Subjective and objective measures of relevance for the description of acoustics conditions on orchestra stages*, Gade points out the relevance of distinguishing between early and late energy: "[...] the early energy from others is useful for ensemble, while the late part provides support to one's own instrument; but the late part also influences the total orchestra loudness which may mask hearing of oneself as well as the useful early sound from others" (Gade, 2013, p. 4).

2.1.2 Masking

Masking is present in both the frequency as well as the time domain and occurs when a sound blocks the ability to hear another sound (Kleiner, 2008, p. 75). For level masking it is important to consider how loud an instrument can get in order to understand the extent of masking. When playing forte a string or wood wind instrument can generate a sound level in free field of about 85 to 95 dB at the ear of the player. Brass players, on the other hand, can generate an additional 10 dB. Depending on how the instrument is held when played, the level could vary significantly between the left and right ear (Meyer & Hansen, 2009, p. 18). Barron concurs with Meyer's investigations and points out that some instrument sections, such as tympani as well as in front of brass, emit high sound pressure levels and therefore masking in these regions is common (Barron, 1993, p. 53). The effect of masking also strengthens the need to investigate directivity of instruments since they emit sound in different directions at various frequencies and this, in turn, could mask sound in other sections. Since this study is limited in using an omni-directional source, no further investigation concerning instrument directivity is performed and the reader is suggested to consult Meyer's work for further reading.

Precedence effect

The precedence effect, or Haas effect, occurs when a sound has a discontinuous or transient character as in music or speech. Localization of the sound source is preliminary due to the direct sound from the source even though reverberation is present. If the reflections are 10 dB louder than that of the direct sound, the precedence effect is negligible (Rossing, 2007, p. 485).

Cocktail Party Effect

The Cocktail Party Effect is the phenomenon when many sources are located in a room and the brain and hearing mechanics have the capability to highlight certain sounds in comparison to others. Nevertheless, in order to be able to locate the source, the sound pressure level has to be about 10 to 15 dB above that of the masking sound (Meyer & Hansen, 2009, p. 17).

Arguably, this concept can also be applied to musicians within an orchestra who have the ability to emphasis certain sounds in order to improve ensemble playing. However, the 10 dB above masking level might make it difficult for certain sections to follow more remote or quiet sections. Furthermore, visual cues from conductor as well as other musicians also play an important role in improving the ability to play in unison.

2.2 Subjective Judgment

In his book *How they sound: Concert Halls and Opera Halls* Beranek makes an attempt to define common terms among musicians and acousticians. The following Table 2.1, tries to pin-point a common language to express subjective judgment in acoustical environments.

Table 2.1: Explanations of subjective parameters according to Beranek (Beranek, 1996, pp. 22 - 26) (Beranek, 2004, pp. 28 - 35).

Subjective parameter	Explanation
Intimacy or presence	Intimacy in an acoustical content could be compared to if a room is visually small, it is generally considered to be more intimate. Intimacy is related to the ITDG, or time between the direct sound and the first reflection, and if the ITDG is short, the hall sounds more intimate than if it is longer (Beranek, 2004, p. 27). However, Rossing states that Beranek does not support this any longer and only states that if the ITDG exceeds 45 ms, the hall is not perceived as intimate (Rossing, 2007, p. 310). Note that the mentioned value for ITDG relates to experiences in the audience and not on stage.
Reverberation or liveness	A hall with longer reverberation is often portrayed as "live", while a hall with shorter reverberation is regarded as "dry" or "dead". If the reverberation is sustained in the region between 350 to 1400 Hz, "Liveness" of the acoustical environment is enhanced (Beranek, 2004, p. 29). On the other hand, if a hall's reverberation is increased in the lower frequency region it is often said to be "warm" (Beranek, 1996, p. 23).

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Table 2.1 – Continued

Subjective parameter	Explanation
Warmth	If a hall is prominent in bass frequencies and an excessively low frequency response is present, it is perceived as "dark" by the musicians. In contrast, a hall might lack bass frequency content due to surfaces such as thin wood panels, organ pipes or even thick upholstery on seats which attenuate lower frequencies. Furthermore, the lack of higher frequencies could even further increase the perception of the hall as being too "dark". Higher frequencies could be absorbed by surfaces in the hall such as draperies or carpets (Beranek, 2004, p. 30).
Loudness	Loudness is the subjective judgment of the volume of a sound. "Strength of sound" is a term used by engineers to describe the loudness in terms of decibels [dB]. If the sound is increased or decreased by 10 dB, it is subjectively judged as a doubling or halving of the strength (Beranek, 2004, pp. 30 - 31).
Timbre	Timbre is the "[...] quality of sound that distinguishes one instrument from another [...]" (Beranek, 2004, p. 31). Additionally, timbre describes how the room effects the frequency content of the sounds heard (Rossing, 2007, p. 310).
Tone Color	Tone color is the balance between various sections of the symphony orchestra. It also includes the balance between low, middle, and high frequencies (Beranek, 2004, p. 31). Therefore, the ceiling reflection could play an important role in the tone color and variations that may occur throughout the orchestra.
Acoustic Glare	Surrounding surfaces and hanging panels such as reflectors could induce a harsh sound unless the surfaces are convex or richly ornamented with small irregularities (Beranek, 2004, p. 31).
Brilliance	Brilliance or "brilliant" sound, is a ringing sound with acoustical qualities that can be described as bright, clear, and rich in harmonics. If a sound contains brilliance, the treble frequencies' decay is decelerated and therefore linger longer in the hall (Beranek, 2004, p. 32).
Balance	Balance could describe both the interplay between different sections within the orchestra as well as the balance between soloists and the entire orchestra. Not only do the surrounding surface geometries and materials effect the balance, but also musical factors such as seating and even conductor's performance have an impact (Beranek, 2004, p. 32).
Blend	Blend indicates how well sounds from instruments mix. The stage's surrounding surfaces and seating arrangement are primary factors of how the sound blends (Beranek, 2004, p. 32).
Ensemble	Ensemble is the ability for musicians of the orchestra to "initiate and release their notes simultaneously so that the many voices sound as one". In order to play in unison, musicians use their hearing but also visual cues to increase ensemble. Through reflectors and other surfaces, the sound energy from different section can be distributed in order to increase their ability to play in unison. Moreover, risers allow for better visual cues and also allow for more visual contact with the audience in the back of the orchestra (Beranek, 2004, pp. 32 - 33).

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Table 2.1 – Continued

Subjective parameter	**Explanation**
Attack	Attack is how the first reflection from surrounding surfaces is judged by the musician in correlation to the direct sound (Beranek, 2004, p. 33).
Texture	Early reflections arrive soon after direct sound and the reflections should be uniformly spaced and numerous in order to create a favorable texture (Beranek, 2004, p. 33).
Echoes	Echoes occur if the reflected sound is delayed too long and the strength of the reflection is loud enough. If the back wall of the concert hall is curved, this could yield focused delayed reflections on stage (Beranek, 2004, p. 33).
Dynamic Range	The dynamic range extends from the background noise level to the sound produced by the musicians. The background noise level is sound produced by audience, noise from ventilation, and even external traffic noise (Beranek, 2004, p. 33).
Tonal quality	Tonal quality implies that the sound transmission from source to receiver has a pure content without any distortion (Beranek, 2004, p. 35).

2.3 Objective Measurements

2.3.1 Reverberation Time

Reverberation time [*RT*] can also be denoted a T_{60} which is the amount of time in seconds it takes for a source to decrease the sound pressure level by 60 decibels [dB]. Commonly, T_{30} is also used which is the amount of time in seconds it takes for a source to decrease the sound pressure level by 30 dB and then extrapolate to a value of 60 dB. Note that T_{30} can be measured in accordance with ISO 3382-1. Furthermore, Meyer suggests that the change in reverberation time is sensed more by the musicians than the audience (Meyer & Hansen, 2009, p. 231). Therefore, this is a factor which should be investigated in the study.

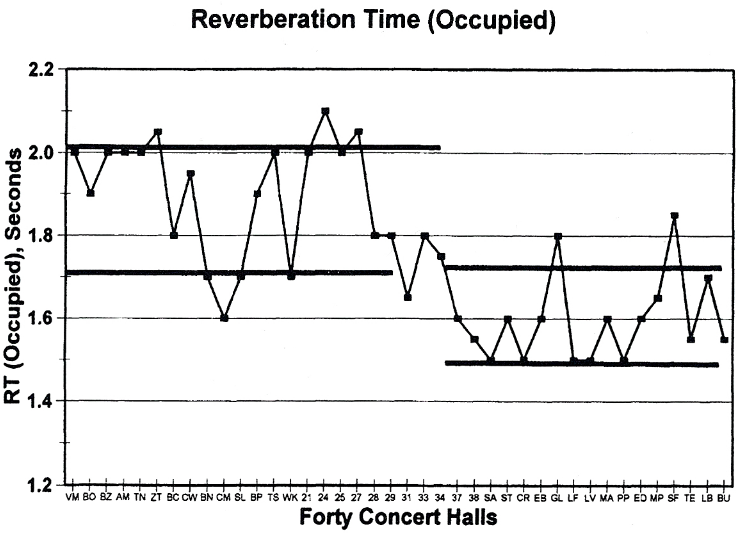

Figure 2.2: RT for 40 occupied concert halls. The x-axis contain concert halls in ranking order (Beranek, 2004, p. 504).

2.3.2 Early Decay Time

Early Decay Time [EDT] is the amount of time in seconds it takes for a sound to decay by 10 dB. This is an important measurement to determine and compare acoustical qualities in concert halls. In order to compare the value with the reverberation time, it is multiplied with six (Beranek, 1996, p. 29). Furthermore, ISO 3382-1 states that *EDT* is related to the perceived reverberance (ISO 3382-1, 2009, p. 15). The just noticeable difference [JND] for *EDT* according to ISO 3382-1 is 5 % with a typical range of 1.0 to 3.0 s (ISO 3382-1, 2009, p. 12).

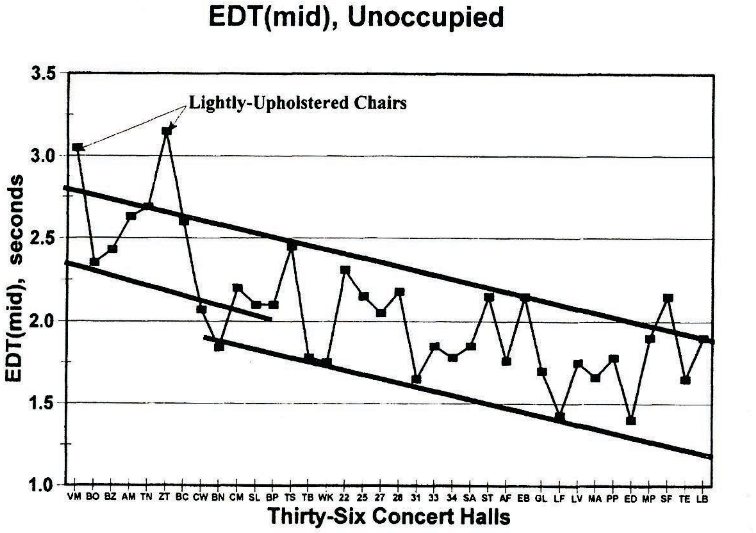

Figure 2.3: EDT for 36 unoccupied concert halls. The x-axis contain concert halls in ranking order (Beranek, 2004, p. 506).

As seen in Figure 2.3, there is a relation between the ranking order and the length of EDT at middle frequencies. In the best halls, an EDT between 2.25 and 2.75 s is expected and in a hall with lower ranked acoustics, the range is expected to fall between 1.4 to 2.0 s (Beranek, 2004, p. 505). Furthermore, lightly-upholstered chairs seem to make a significant difference in the measured EDT of unoccupied halls and these values are most likely more within the range of expected values when an audience is present. One could argue that halls with lightly-upholstered chairs might effect the stage acoustics during rehearsals when not enough sound is absorbed and the difference between the acoustics during rehearsal and concert is too great. Of course, these values are most likely related to the audience's listening experience and the expected values on stage may differ.

2.3.3 Initial-Time Delay Gap

Initial-Time Delay Gap [ITDG] is a measure of delay between the direct sound and the first early reflections as seen in Figure 2.1 on page 2. ITDG has a preferred value of down to 25 ms at the middle of the audience for a hall with acoustics that are considered excellent. For halls that are ranked lower ITDG may exceed 35 ms and for halls with unsatisfactory acoustic values might exceed 60 ms (Beranek, 2004, pp. 27 - 28). Very little is know about the ITDG on stage, 25 ms would result in a path length of approximately 8.5 m and 60 ms in 20.6 m it may therefore be concluded that this measurement is of little interest in stage acoustics. However, Figure 2.4 is included in order to illustrate the relation between ranking halls and the ITDG in the audience area.

2.3.4 Support

Support [*ST*] is a measure that represents to what degree a musician is able to hear one self or other instruments close by. Leo Beranek states in his book *Concert Halls and Opera Houses: Music, Acoustics, and Architecture* that "When a canopy is used to create a favorable ST1 on stage, its height should be between 7 to 13 m, adjusted according to the orchestra's preference. Depending upon what energy is reflected from other surfaces

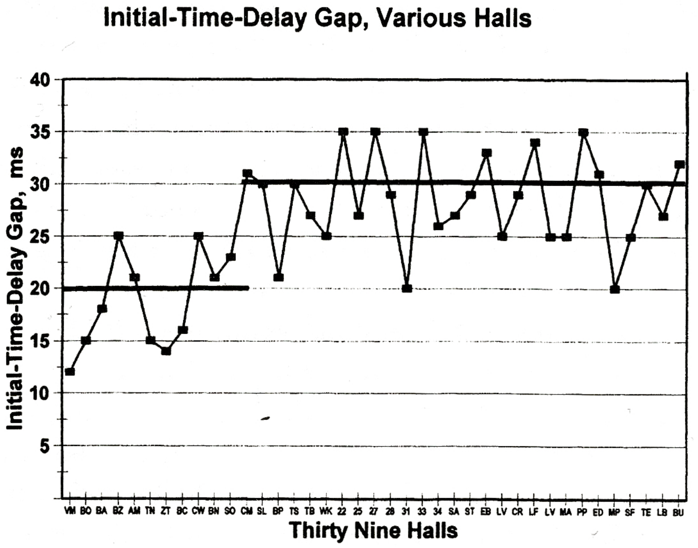

Figure 2.4: ITDG for 39 unoccupied concert halls. The x-axis contain concert halls in ranking order (Beranek, 2004, p. 519).

this height will make ST1 equal approximately to -12 to -15 dB" (Beranek, 2004, p. 538). ST_{early}, also denoted $ST1$, considers the reflected energy in the time intervals according to equation (2.1) and relates to the subjective judgment of ensemble. According to ISO 3382-1, the typical range of the ST_{early} is between -24 dB to -8 dB and is averaged over the octave bands between 250 to 2000 Hz (ISO 3382-1, 2009, p. 23).

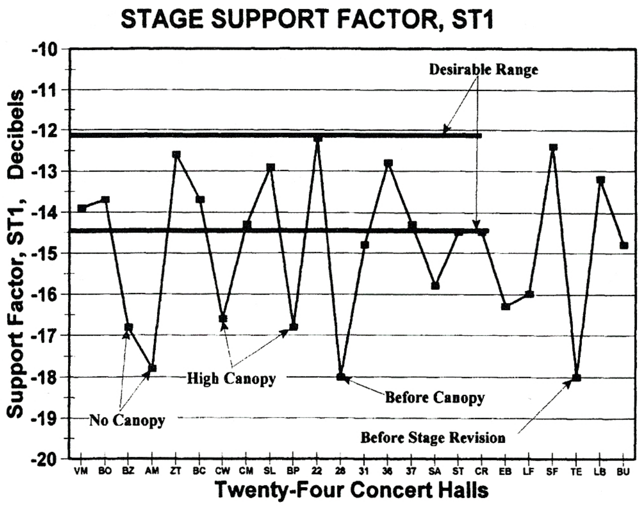

Figure 2.5: ST1 or ST_{early} for 24 unoccupied concert halls. The x-axis contain concert halls in ranking order (Beranek, 2004, p. 539).

$$ST_{early} = 10 \log \frac{E_e(20 - 100ms)}{E_e(0 - 10ms)} = 10 \log \frac{\int_{20}^{100} p^2(t)\, dt}{\int_0^{10} p^2(t)\, dt} \tag{2.1}$$

Receiver and source should have a height of 1.5 or 1.0 m. Reference is the level of the direct sound and the floor reflection summed up in the time span between 0 to 10 ms. Moreover, in order to avoid early reflections before 20 ms, the transducer should be placed at least 4 m away from any reflecting surface (Dammerud et al., 2010, p. 2). In contrast to ST_{early}, ST_{late} accounts for later reflections in the measurement according to equation (2.2). Moreover, ST_{total} considers both the early and late energy emitted by the source according to equation (2.3). Finally, the time span between the different ST measurements is illustrated in Figure 2.6.

$$ST_{late} = 10\log\frac{E_e(100-1000ms)}{E_e(0-10ms)} = 10\log\frac{\int_{100}^{1000} p^2(t)\,dt}{\int_0^{10} p^2(t)\,dt} \tag{2.2}$$

$$ST_{total} = 10\log\frac{E_e(20-1000ms)}{E_e(0-10ms)} \tag{2.3}$$

According to Dammerud, ST_{early} and ST_{late} measurement are less accurate than that of G_{early} and G_{late} (Gade, 2013, p. 3). Gade does not agree with the statement and in his article *Suggested data collection for assessing the stage conditions on symphony orchestra stages* he claims that ST is still a valid measurement (Gade, 2011, p. 3).

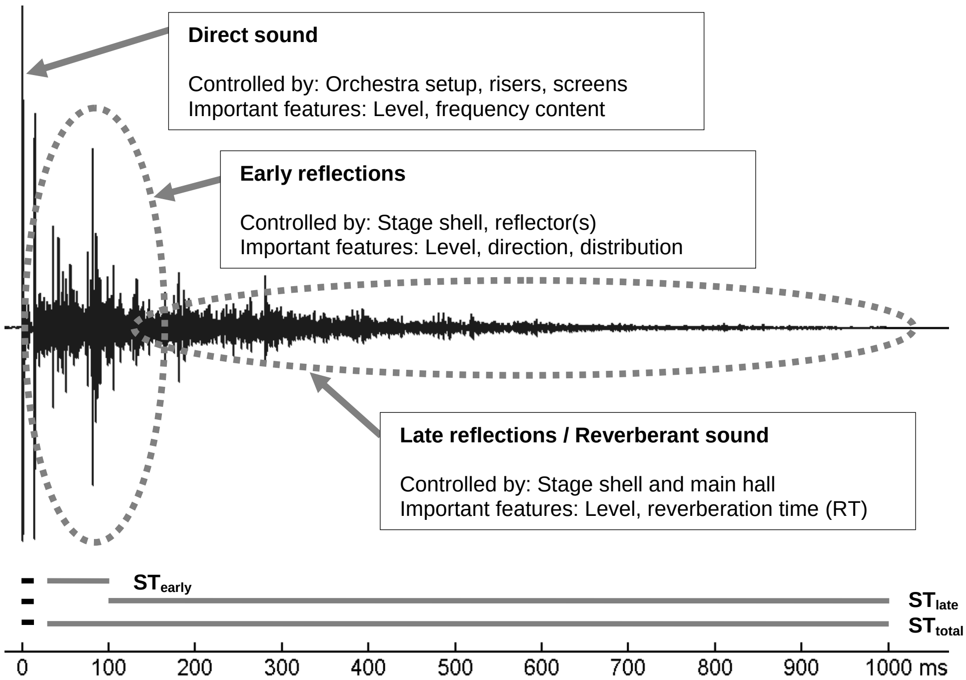

Figure 2.6: Illustration of the time spans in the reflectogram and corresponding time span for support value (Dammerud, 2006, p. 6).

Wenmaekers et al., have proposed an alternative measure of ST_{early} namely $ST_{early,d}$ which is shown in equation (2.4). In contrast to ST_{early}, $ST_{early,d}$ is able to account for attenuation of the sound over larger distances within the orchestra. Moreover, it also includes the negative influence of the delay of the direct sound which is neglected in the strength parameters G (Gade, 2013, p. 3).

$$ST_{early,d} = 10\log\frac{\int_{10}^{103-delay} p_d^2(t)\,dt}{\int_0^{10} p_{1m}^2(t)\,dt} \tag{2.4}$$

The difference between ST_{early} and $ST_{early,d}$ is that the numerator is integrated between 10 ms (instead of 20 ms as in ST_{early}) and a time variable called $103 - delay$. The integration starts at 10 ms in order to account for energy reflected from surfaces at a distance of 4 m from the rec position (Gade, 2013, p. 4). The definition of $103 - delay$ is the distance between the source $[src]$ and receiver $[rec]$ divided by the speed of sound, which yields the time it takes for the direct sound to travel from the src or the rec[1] (Wenmaekers & Hak, 2013, p. 3). According to Wenmaekers, $ST_{early,d}$ seems to correlate better than ST_{early} with the musicians' preferences for the measured halls that have high early reflections. However, he concludes that further investigations are needed in order to conclude any subjective correlations (Gade, 2013, p. 4).

[1]Note that for integration purposes the time limit should have a unit in ms.

Consequently, Wenmaekers et al. have also proposed a change of ST_{late} to $ST_{late,d}$ according to equation (2.5). Similarly, the numerator is integrated from the calculated time variable $103 - delay$ to the time that the decay reaches the noise floor of the hall.

$$ST_{late,d} = 10 \log \frac{\int_{103-delay}^{\infty} p_d^2(t)\, dt}{\int_0^{10} p_{1m}^2(t)\, dt} \tag{2.5}$$

2.3.5 Early Ensemble Level

Early Ensemble Level [EEL] takes even earlier energy into consideration and is a suitable measurement for smaller stage areas, see equation (2.6). In comparison to ST, EEL is more difficult to correlate to musicians' perception. The problem partly lies in that since EEL also considers the direct sound and early reflections up to 20 ms, the furniture and musicians between the *src* and *rec* play an important role in the sound field present on stage (Dammerud et al., 2010, p. 11). Performing measurements with furniture and musicians present is rare due to the cost and coordination needed, hence EEL might not be the best choice.

$$EEL = 10 \log \frac{E_e(0 - 80ms)}{E_e(0 - 10ms)} \tag{2.6}$$

2.3.6 Clarity

Clarity [C_{80} or C_{50}], is defined as the ratio between the early energy to the late energy according to equation (2.7) and is highly correlated inversely to the reverberation time. Clarity is measured in dB and ISO 3382-1 states that the JND is 1 dB. Often published C_{80}-values are averaged over three octaves bands namely: 500, 1000, and 2000 Hz. Henceforth, this average value is denoted $C_{80}(3)$. However, ISO 3382-1 only suggests an average between 500 an 1000 Hz and a typical range between -5 to +5 dB. During rehearsals, when the hall is unoccupied, an expected value of $C_{80}(3)$ should have a value between +1 to + 5 dB. This allows for details in the music to be heard more clearly. In contrast, during performance, an expected value of -1 to -4 dB might be considered appropriate. Furthermore, increased clarity contributes to rapidly played passages for instruments such as the violin (Beranek, 2004, pp. 526 - 527). Note that C_{80} can be measured in accordance with ISO 3382-1. The ISO-standard suggests measurements to be performed in the audience area, but the method can also be applied to measure in the stage area (Gade, 2013, p. 3).

$$C_{t_e} = 10 \log \frac{\int_0^{t_e} p^2(t)\, dt}{\int_{t_e}^{\infty} p^2(t)\, dt} \tag{2.7}$$

It may be noted that C_{80} with $t_e = 80ms$ is usually used in room designed for music, while C_{50} with $t_e = 50ms$ is usually used in rooms for speech.

2.3.7 Definition

In contrast to clarity, definition [D_{50}] is the ratio between early (up to 50 ms) and total sound energy according to equation (2.8). Note that unlike clarity which is measured in dB, definition is a percentage. There is also a relation between C_{50} and D_{50} which is displayed in equation (2.9). Due to this close relationship between C_{50} and D_{50} one would expect a high correlation between clarity and definition.

$$D_{50} = \frac{\int_0^{50} p^2(t)\, dt}{\int_0^{\infty} p^2(t)\, dt} \tag{2.8}$$

$$C_{50} = 10 \log \frac{D_{50}}{1 - D_{50}} \tag{2.9}$$

2.3.8 Lateral fraction

Lateral fraction [LF] is defined as the ratio between the instantaneous sound pressure measured with a figure-of-eight characteristic microphone integrated from 5 to 80 ms and the sound pressure measured with an omni-directional characteristic microphone integrated from 0 to 80 ms according to equation (2.10). Note that the LF is often used in measurements in the audience, but not on stage.

$$LF = \frac{\int_5^{80} p_8^2(t)\, dt}{\int_0^{80} p^2(t)\, dt} \tag{2.10}$$

2.3.9 Bass Ratio and Treble Ratio

Bass ratio [BR] is defined as the ratio between two RTs [2] according to equation (2.11). In halls with longer RT, a value between 1.10 and 1.25 is preferred. While in a concert hall with RT shorter than 1.8 s a value of 1.10 to 1.45 is preferred (Beranek, 1996, p. 513).

$$BR = \frac{RT_{125Hz} + RT_{250Hz}}{RT_{500Hz} + RT_{1000Hz}} \tag{2.11}$$

Beranek claims that BR does not correlate with rating categories, therefore another measurement for warmth should be found (Beranek, 2004, p. 512). Beranek's second attempt to find an objective parameter which corresponds to warmth lead him to measurements of strength. In a similar way to BR the Treble Ratio [TR] is defined according to equation (2.12) (Rossing, 2007, p. 310).

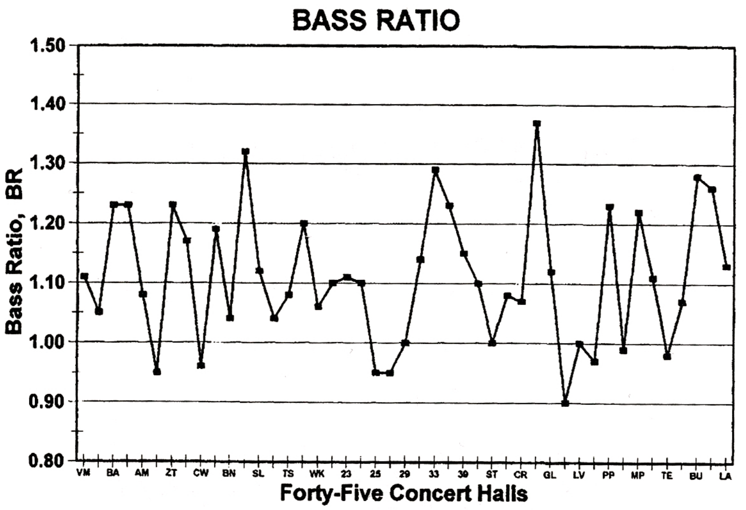

Figure 2.7: BR for 45 unoccupied concert halls. The x-axis contain concert halls in ranking order (Beranek, 2004, p. 517).

$$TR = \frac{RT_{2000Hz} + RT_{4000Hz}}{RT_{500Hz} + RT_{1000Hz}} \tag{2.12}$$

2.3.10 Strength

In his attempt to find an objective parameter for warmth, Beranek investigated 38 unoccupied concert halls and measured the Strength [G], also called Gain, at mid- and low-frequencies. Supposedly, the mathematical difference between between the two or $(G_{125} + G_{250}) - (G_{500} + G_{1000})$ could help determine a relation between warmth G. This study was not conclusive and Beranek made another attempt. The third attempt involved measurements of G_{low} a.k.a. G_{125} which showed a relation between warmth and the objective measurements in Bradley's and Soulodre's laboratory study (Beranek, 2004, pp. 512 - 513).

In contrast to ST, G can be used to measure larger *src-rec* distances than 1 m. However, it is relevant to consider the position combinations instead of averages as is done with ST (Gade, 2013, p. 5). ISO 2232-1,

[2]Note that the RT is measured in an occupied room. BR can also be calculated based on G values (Rossing, 2007, p. 310).

states how G should be measured and the following equation (2.13) illustrates how the measurement should be performed.

$$G = 10\log\frac{\int_0^\infty p^2(t)\,dt}{\int_0^\infty p_{10}^2(t)\,dt} = L_{pE} - L_{pE,10} \tag{2.13}$$

L_{pE} is the sound pressure level at the measurement position according to equation (2.14).

$$L_{pE} = 10\log\frac{1}{T_0}\int_0^\infty \frac{p^2(t)\,dt}{p_0^2} \tag{2.14}$$

$L_{pE,10}$ is the sound pressure level in free field at a 10 m distance from the source.

$$L_{pE,10} = 10\log\frac{1}{T_0}\int_0^\infty \frac{p_{10}^2(t)\,dt}{p_0^2} \tag{2.15}$$

Where: $p(t)$ is the impulse response's measured sound pressure at the measurement position. $p_{10}(t)$ is the impulse response's sound pressure in free field measured at a distance of 10 meters from the source. p_0 is the reference pressure which is equal to 20 μPa. T_0 is a reference time of 1 s.

The definition of the late strength [G_{late}] is stated in equation (2.16) as the ratio of the sound energy after 80 ms to the direct sound energy distributed from an omnidirectional source at a distance of 10 m. Moreover, the relation to G and C_{80} is also defined (Gade, 2013, p. 2).

$$G_{late} = 10\log\frac{\int_{80}^\infty p^2(t)\,dt}{\int_0^\infty p_{10}^2(t)\,dt} = G + 10\log\frac{10^{C_{80}/10}}{1+10^{C_{80}/10}} \tag{2.16}$$

In the equation for early strength [G_{early}], the numerator's time span extends from 0 to 80 ms and the denominator remains the same as in G_{late} according to equation (2.17).

$$G_{early} = 10\log\frac{\int_0^{80} p^2(t)\,dt}{\int_0^\infty p_{10}^2(t)\,dt} = G + 10\log\frac{1}{1+10^{C_{80}/10}} \tag{2.17}$$

In the previous section is was mentioned that BR is not a suitable measurement to indicate the warmth of a concert hall. G_{125} is a measure which yields good correlation with ranked concert halls, see Figure 2.8 (Beranek, 2004, p. 513). In contrast to G_{125}, Figure 2.7 does not indicate any significant correlation between the ranking of halls and BR. Therefore, as a measure of warmth on stage G_{125} could yield a better result for stage acoustics than BR.

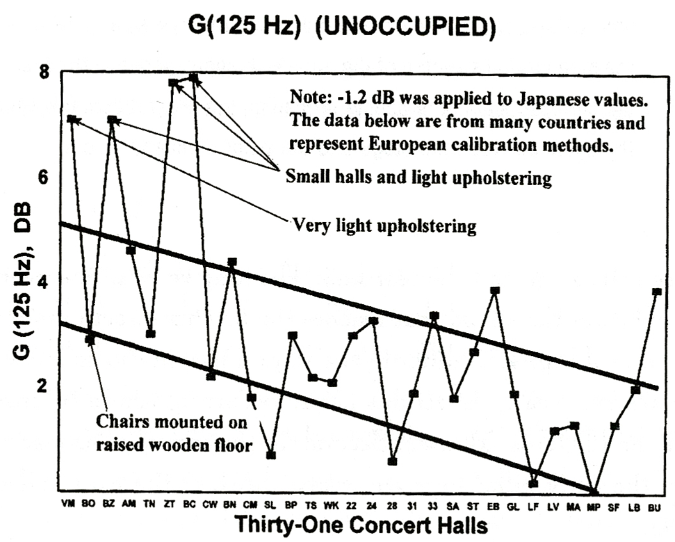

Figure 2.8: G_{125} for 31 unoccupied concert halls. The x-axis contain concert halls in ranking order (Beranek, 2004, p. 517).

2.4 Previous Research

Since the beginning of the 80's, Anders Gade has been active in research concerning the development of the understanding concert hall acoustics. Through factor analysis Gade managed to correlate objective parameters and prove that RT, EDT and C_{80} are tautological. Moreover, Gade made studies in several concert halls concerning ensemble and developed the stage support measurement [ST]. ST measures how much of a musician's emitted sound energy that is reflected to a fellow musician sitting at a distance of one meter (Beranek, 1996, p. 46).

Dammerud completed his Ph.D. Thesis concerning stage acoustics and the correlation between subjective and objective parameters. Although, Dammerud did not manage to find anything significant in the correlation between the subjective judgments of musicians and objective measurements in concert halls, he did find geometrical parameters of the the hall which correlated to the musicians' subjective responses (Gade, 2013, p. 6).

Through recording of impulse responses and experiments in an anechoic chamber, Ueno concluded that a high amount of early reflections is disliked by many musicians because it masks the reverberation and makes a room sound "small". The high amount of early reflections correspond to an ST_{early} value in the range between -10 to -7 db. Moreover, long reverberation was perceived as helping "making music", but loud reverberation decreased to capability for ensemble playing (Gade, 2011, p. 5).

Naylor suggested the use of a Modulation Transfer Function [MTF] in order to measure the clarity of OTHER sounds. However, in his studies he managed to conclude that the level ratio is more important than clarity due to MTF. Furthermore, Naylor performed studies on the balance between one's own (SELF) and the level of other instruments in the surrounding (OTHER). Naylor found that both SELF and OTHER could be heard better if the level of OTHER was between -15 to -8 dB relative to SELF (Gade, 2011, p. 5).

In 2013, Behzad Ranjbari completed his thesis at Chalmers University of Technology suggesting two new types of metrics when evaluating stage acoustics in concert halls. Ranjbari proposed the use of G_{self} and G_{other}. In comparison to currently used measures for stage acoustics such at ST, G_{self} and G_{other} claims to consider measurements across the stage, directional characteristics of instruments, distance from instrument to ears, masking, and avoids averaging along measurement positions. (Ranjbari, 2013, p. 35) However, there is no consideration between the early and late part of the energy which might be questionable (Gade, 2011, p. 4). Furthermore, this has only been used in one concert hall and the reliability of these metrics have not been fully evaluated.

2.5 Design of stages for symphonic orchestras

2.5.1 Instrument groups and seating arrangements

There are about 100 musicians in a full symphonic orchestra and the musicians are divided into four main instrument groups. Locations of the instruments can vary, but a general position as well as the division of instruments is also shown in Table 2.2. Strings are often positioned to the side and in front of the conductor. The section most likely covers the width of the stage. Risers usually elevate the woodwinds and horn section which is located behind the strings. Located at the back in close proximity of the rear wall of the stage are the heavy brass and percussion (Meyer & Hansen, 2009, p. 264).

Table 2.2: The main instrument groups and their attributes.

Instrument Group	Instruments	General location
Strings	Violins, violas, celli, double basses, (piano)	Front
Woodwind	Oboes, bassoons, clarinets, flutes	Middle
Brass	Trumpets, french horns, trombones, tubas	Back
Percussion	Timpani, vibraphone, harps, piano	Back

Typically, three types of seating arrangements for the strings are used in concert halls for symphony orchestras. In Figure 2.9, all three options are shown including the American, the Alternative American (Furtwängler's), and German (European) (Meyer & Hansen, 2009, p. 265). Furthermore, the most common of the three is the American arrangement which is shown in Figure 2.10 together with other instrument groups such as woodwind and percussion.

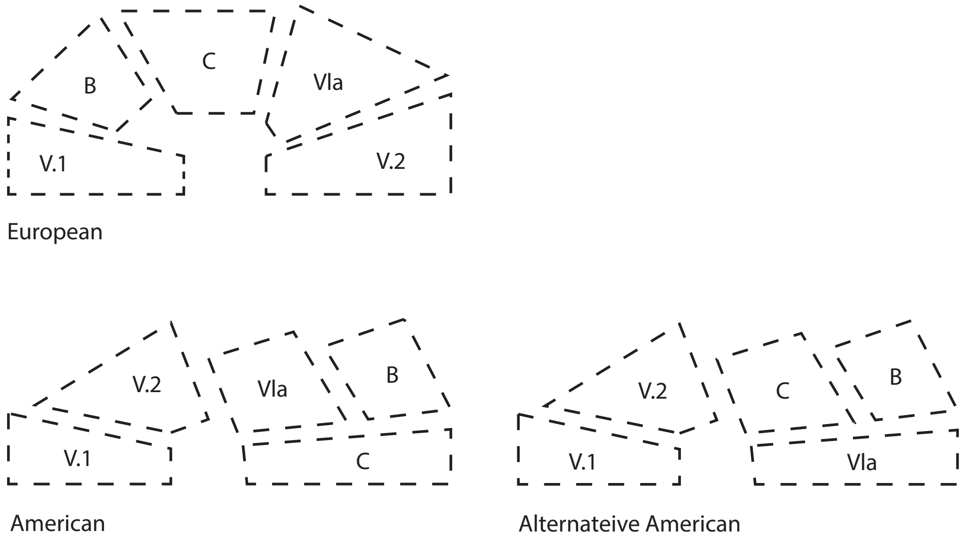

Figure 2.9: Seating arrangements: American, Alternative American, and German. V.1: first violins, V.2: second violins, Vla: violas, C: Celli, B: double basses.

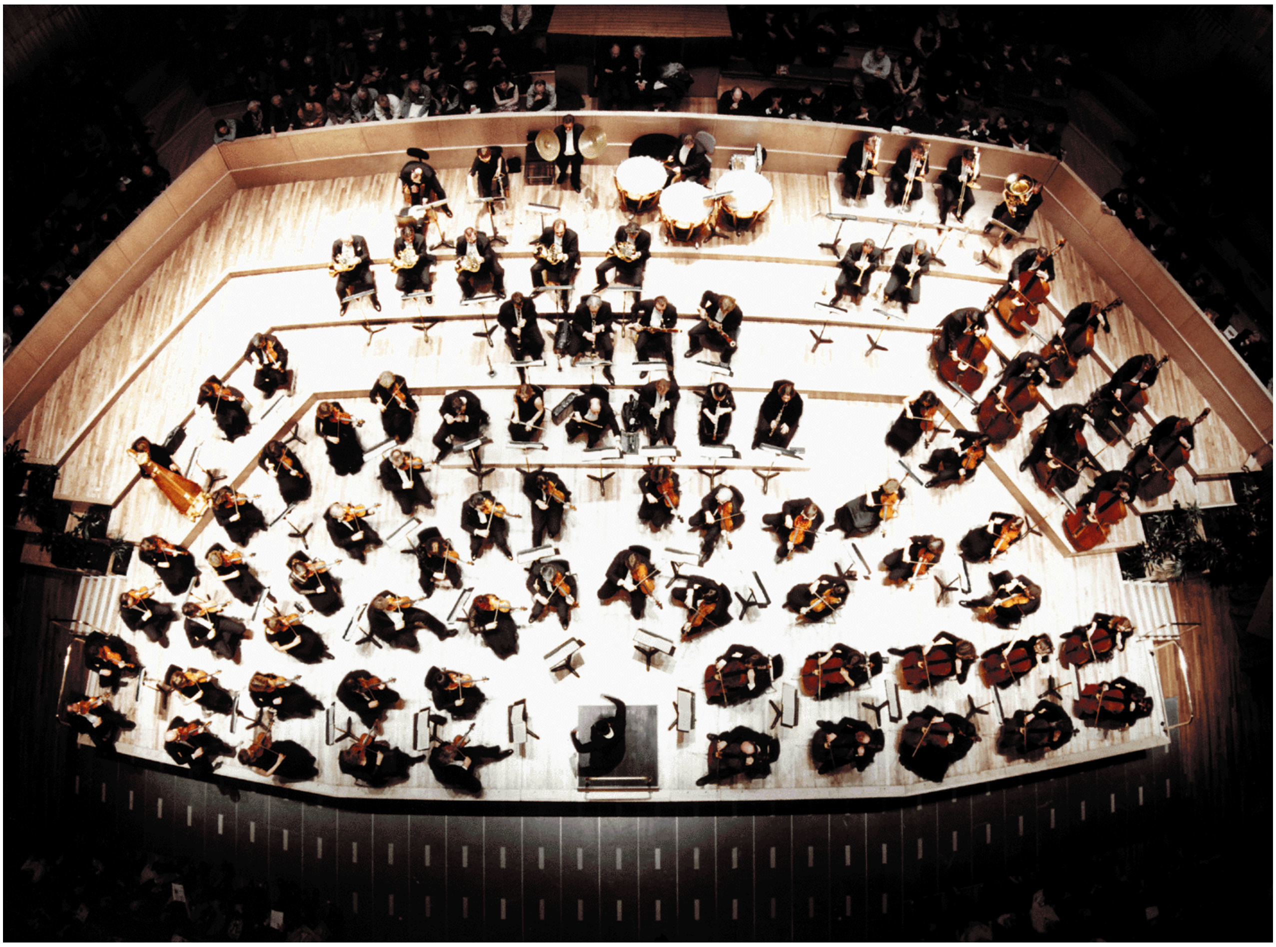

Figure 2.10: Symphony orchestra configured according to the American seating arrangement Hugill (2001).

In his book *Auditorium Acoustics and Architectural Design* Michael Barron lists areas that each instrument group takes up per person, see Table 2.3. This is important to consider in the stage design because it effects the musician considerably if there is not enough room.

If a full symphony orchestra is performing, a stage area of 150 m^2 is suggested in accordance with required space for each individual instrument (Beranek, 2004, p. 544). Barron suggest an increase of 150 m^2 to 200 m^2 for a full symphony orchestra. This is due to several reasons. Firstly, the additional 50 m^2 of space should compensate for lost space due to risers or access routes on the stage. In addition, a narrow band of one meter at the front edge of the stage is suggested in order to gain better access. Secondly, supplementary space for soloist and extra percussion. Finally, space at the side walls and back in order for instruments such as the french horn to be more comfortable (Barron, 2009, p. 57).

Table 2.3: Required area depending on type of instrument (Barron, 2009, p. 57).

Area [m^2]	Instruments
1.25	upper strings and wind instruments
1.5	cello and larger wind instruments
1.8	double bass
10	tympani
20	or more for other percussion instruments

Nevertheless, ease of ensemble playing is decreased as the delay of the direct sound increase. According to Gade, at a distance of 8 meters or more the delay of the direct sound starts to effect the ensemble playing (Barron, 1993, p. 52). Therefore, reducing the distance between musicians should be an early consideration in the stage design and may be a contrast to the amount of space required.

2.5.2 Surrounding surfaces

Stage design including geometry of surfaces and material choice plays a vital role in creating the acoustical environment. The musicians' concern, according to Gade, lies in two primary parts. Firstly, the need to hear each other, or meet necessary conditions for improved ensemble is important. Secondly, the need to have good support from the musicians' own instruments (Barron, 2009, pp. 56 - 57). Since the direct sound from instruments are not enough to distribute energy throughout the orchestra, reflections from surrounding surfaces play an important role.

Reflections which arrive 10 ms after the direct sound or earlier sound are perceived as disturbing. Optimal delay is considered to be between 17 and 35 ms. On the other hand, instrumental soloists find it favorable for later reflections in the time region of 20 to 100 ms, even reflections as late as 200 ms could be seen as favorable. Moreover, reflections aid in intonation in the base and mid frequency range (Meyer & Hansen, 2009, pp. 224 - 229).

Usually, reflections from the ceiling are not enough to evenly distribute the sound energy throughout the orchestra. Therefore, additional reflectors can be suspended above the orchestra. The recommended suspension height for the reflectors is at about a distance of 8 m, although somewhere between 6 to 12 m is considered satisfactory (Meyer & Hansen, 2009, p. 225). Undoubtedly, the material composition of the reflectors should allow for a sufficient amount of reflections and have a higher density. Reflectors that are made of thin cellophane, or other types of light weight material, tend to absorb lower frequencies.

Dimensions of stage

For a 200 m^2 stage, the width should not exceed 18 m which in turn yields a depth of 12 m (Barron, 2009, p. 58). Only the amount of area required for a symphony orchestra is included and an addition of a choir would increase the stage area considerably. If a seated choir of 100 singers is present, it would require an additional area of about 50 m^2 (Barron, 2009, p. 57). The choir is often placed behind the symphony orchestra but may also be located in other parts of the concert hall depending on the design.

The previously mentioned requirements are valid for an orchestra of 100 people but it is not uncommon that far less musicians are performing. Therefore, at times, the stage would have to be smaller in order to decrease the delay of reflections coming from side- and back walls. Therefore, a flexible system which allows for surfaces to be moved is desirable (Barron, 2009, p. 58).

Walls

According to Meyer, a large orchestra should be placed as close to the wall as possible in order to decrease the distance for the musicians sitting in the middle. This statement further supports the claim for the usefulness of a movable wall system. If the distance is too large, this might cause trouble for the conductor or the front strings because the rear strings are too weak and cannot be heard (Meyer & Hansen, 2009, p. 225).

Acoustics on stage can be altered through changing angles of walls. For instance, the upper part of walls surrounding the stage can be tilted downwards (Barron, 2009, p. 59). Minimum height of walls surrounding the stage area varies, but somewhere between 1.8 and 3 m is common. If the wall is higher, it generally contributes to the reflection of lower frequencies (Meyer & Hansen, 2009, p. 225). Furthermore, balconies can also be tilted downwards and towards the stage in order to increase reflections (Barron, 2009, p. 59).

It is important to keep in mind that in larger halls, strong reflection could cause the musicians to overestimate the loudness in the audience. In turn, a loud sound on stage might not be enough for the listener in the audience (Meyer & Hansen, 2009, p. 226).

Floor and risers

In areas such as in front of the brass section or tympani, the increase in sound pressure levels is an important consideration. These places might have to be adjusted through the use of risers or screens in order to decrease the sound level to other parts of the orchestra (Barron, 2009, p. 57).

The height of the risers should be at about 100 mm at the middle and then higher at the back. The depth of the riser is also important in order to maximize the use of space. It is recommended that upper strings and woodwinds have a depth of 1.25 meters, while brass and cellos require 1.4 meters. Double basses require even more space, but this can be decreased by placing music stands on the riser in front. Percussion and tympani should have a depth of around 1.4 meters (Barron, 2009, pp. 58 - 59). As for the floor construction, it is regarded that platform thickness of 25 mm, joist spacing of 600 mm at least (Barron, 2009, p. 59).

2.5.3 Geometrical data

Dammerud suggests a collection of architectural data of geometries on stage in order to evaluate relationships to subjective judgment of musicians. The overall acoustic impression [OAI] has been found to have correlation to the geometrical data as seen in Figure 2.11 (Dammerud et al., 2010, p. 4). However, this thesis does not cover a study of geometrical data since Dammerud has already found high correlation among even more halls in this doctoral thesis. In Figure 2.11, certain geometrical measures are displayed which are recommended by Dammerud to consider in concert hall design in order to improve subjective opinions of musicians.

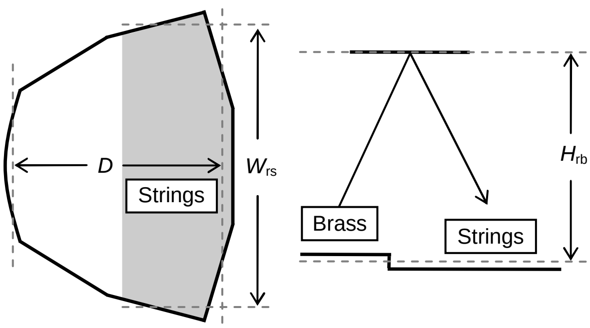

Figure 2.11: Architectural data used to assess stage acoustics by Dammerud (Dammerud et al., 2010, p. 4).

2.6 Concert Halls

This section includes data concerning the top-rated concert halls according to Beranek's studies in his book *Concert Halls and Opera Houses* in Boston, Vienna, and Amsterdam. Beranek only includes one hall from Sweden which is located in Gothenburg which is not relevant to this study. The six halls studied in this thesis is also presented which are located in the cities of Jönköping, Gävle, Malmö, Västerås, and Vienna. Note that

Malmö has both the current hall as well as the new concert hall currently being constructed. Basic collected data from the different halls is found in Table 2.4. [3]

According to Beranek's ranking system for concert hall acoustics, the top five halls include: Grosser Musikvereinsaal in Vienna, the Symphony Hall in Boston, Teatro Colón in Buenos Aires, Konzerthaus in Berlin, and Concertgebouw in Amsterdam. Three of these halls, namely the halls in Boston, Vienna, and Amsterdam have been chosen to be investigated further due to high quality stage acoustics.

Table 2.4: Data concerning the halls listed in Beranek's literature as well as halls included in this study (Beranek, 1996, pp. 79 - 82).

Concert hall	Year	Seats	Hall dimensions l x w x h [m]	Volume [m^3]	Stage area [m^2]	Stage dimensions w x l [m]
Boston Symphony Hall [BO]	1900	2625	39 x 23 x 19	18750	152	N/A
Amsterdam Concertgebouw [AM]	1888	2037	26 x 28 x 17	18780	160	N/A
Gävle Konserthus [GV]	1998	820	31 x 24 x 17	10500	210	N/A
Jönköping SPIRA [JKPG]	2011	820	33 x 22 x 18	13000	187	17 x 11
Malmö Konserthus [MÖ-C]	1985	1200	N/A	N/A	286	22 x 13
Malmö KKH [MÖ-N]	2015	1600	47 x 23 x 19	20500	266	19 x 14
Västerås Konserthus [VST]	2002	917	37 x 20 x 16	9600	190	N/A
Vienna Musikvereinsaal [VM]	1870	1680	36 x 20 x 17	15000	163	N/A

2.6.1 Boston, symphony hall

In the Boston Symphony Hall [BO], the rear and side walls restrict the stage dimensions. The ceiling also acts as a diffusive surface at higher frequencies. Therefore, reflections back to the orchestra at the higher frequency range occurs (Meyer & Hansen, 2009, p. 227).

Musicians appreciate the acoustics on stage due to excellent balance, blend, and ensemble. However, risers are most likely not possible to install with a full symphony orchestra because of the small stage area of only 149 m^2. If more stage is needed, for instance when a choir or soloists are performing, an extension of the stage is needed. It is possible to extend the stage by almost 1.52 m in such cases (Beranek, 2004, p. 542). The side walls are splayed at an angle of nearly 20 degrees and the width of the stage averages at about 15.2 m. The ceiling has an average height of 13 m and a slope of 15 degrees (Beranek, 2004, p. 542). Basic data about the Symphony Hall in Boston is found in Table 2.4.

BO has a reverberation time that is 0.1 s shorter than that of VM and AM, although, it has a larger volume than VM and AM. However, the sound level on stage is about 1 to 2 dB higher on stage due to the orchestra enclosure (Beranek, 2004, p. 543).

2.6.2 Vienna, Musikvereinsaal

In the Musikvereinsaal in Vienna [VM], the rear wall and side walls reflect the sound energy early. Also, the surround gallery and walls contribute further in an increase of early reflections (Meyer & Hansen, 2009, p. 226).

VM has no stage enclosure, only three walls surround the stage as well as a balcony. The area of the stage is slightly bigger than that of BO at 163 m^2. Moreover, the stage area is adequate according to Barron's guidelines for stage size. The average height of the ceiling is 15.2 m, which is comparable with BO. Furthermore, the distance between side walls is similar to that of the BO with just an additional meter from the center line. (Beranek, 2004, p. 543) Information about the Musikvereinsaal in Vienna is displayed in Table 2.4 (Beranek, 1996, pp. 377 - 380).

An organ at at the back of the stage partly absorbs sound, and the lack of enclosure might be considered to reduce the quality of the sound environment on stage. However, investigations by Gade in 1989 and Bradley in 1994 showed that the conditions on stage in VM are similar to those in BO (Beranek, 2004, p. 543).

[3] Note that dimension are give in meters rounded off to the nearest whole number. They are displayed as length times width times higher in accordance with: l x w x h.

2.6.3 Amsterdam, Concertgebouw

The AM stage area is 160 m^2 and the distance between conductor and musicians on stage are less than 9 m. The ceiling height in AM is 16.8 m which is similar to both BO and VM. However, the width of the stage is almost twice as wide with the average distance from the center line of the stage to the walls is 14.6 m totalling a width of 29.2 m. This great distance yields a longer distance for the sound reflection and delay the amount of yearly reflections. Plans and sections are seen in Figure C.1 and Table 2.4 shows basic geometrical and acoustic data of the hall (Beranek, 2004, pp. 542 - 543).

In contrast to BO and VM, AM has 4 dB less sound reflecting from surrounding surfaces which creates a difference in the sound field on stage. The measurement includes a musician sitting at the center line and a person 1 m at the side produces the sound. The conductor's sound field is less clear due to lack of early reflections. Furthermore, the lack of clear sound and early reflections make it difficult for ensemble. If a visiting orchestra is playing in AM, there is usually a need for special rehearsals prior to the performance in order to adjust to the acoustic conditions on stage. Since the acoustics is different, the need to have visual contact with the conductor is vital (Beranek, 2004, pp. 542 - 543).

2.6.4 Gävle

Reflectors are suspended from the ceiling with variable height and the angle of the reflectors can be adjusted. Draped curtains are located above the first floor balcony in order to configure the acoustics depending on the type of orchestra arrangement, see Figure 2.12. The walls surrounding the stage are slightly convex in order to diffuse the sound, see Figure 2.13. Information about Gevaliasalen in Gävle is displayed in Table 2.4 (Olofsson, 2013, p. 36).

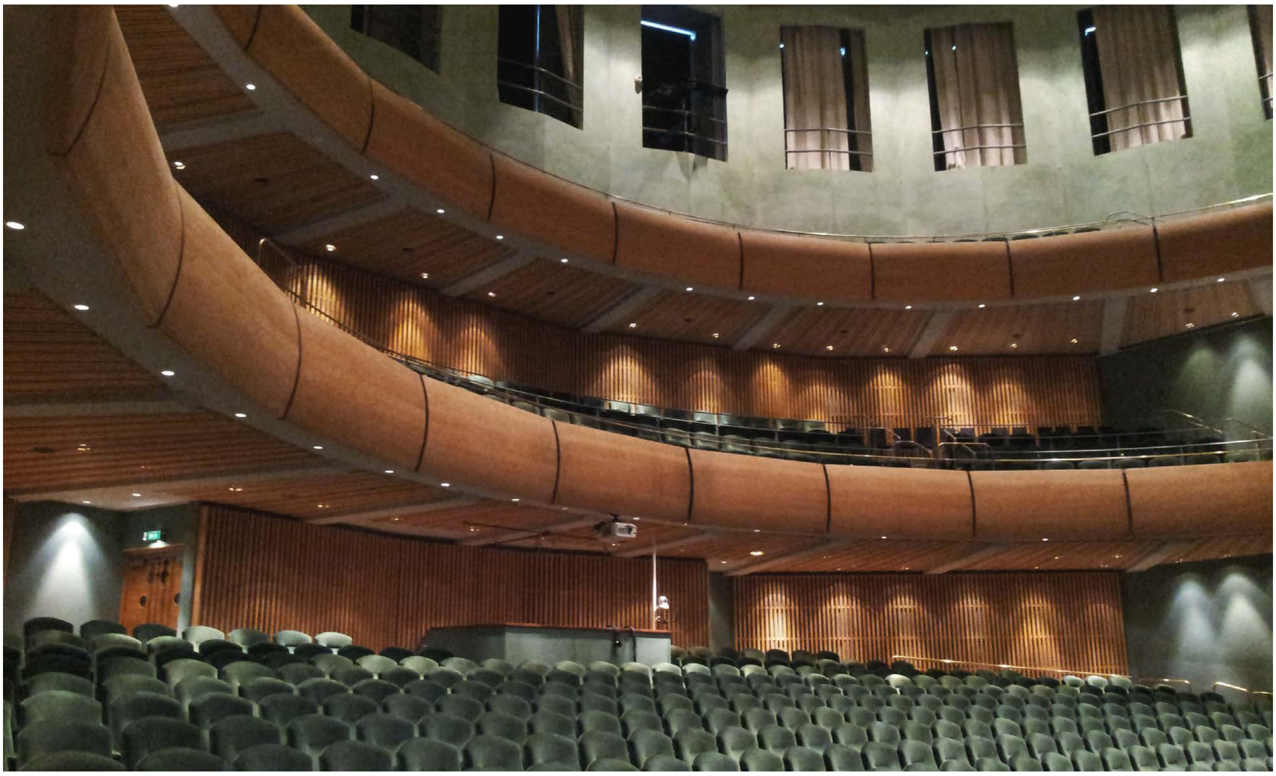

Figure 2.12: Image representing balconies, seating, and absorptive curtains in Gävle.

2.6.5 Jönköping

Information about stora salen in Jönköping is displayed in Table 2.4 (Olofsson, 2013, p. 44). The concert house is more specifically known as SPIRA.

Figure 2.13: Stage in Gävle concert hall with furniture and risers.

Figure 2.14: Jönköping's audience as well as back- and side-walls (Olofsson, 2013, p. 39).

2.6.6 Malmö

In contrast to the other halls, Malmö houses a full symphony orchestra of 90 musicians. Basic data about the hall is found in Table 2.4 MSO (n.d.).

Figure 2.15: The stage of the current Malmö concert with set-up for a full symphony orchestra.

2.6.7 Västerås

Reflectors suspended from the ceiling are adjustable in height and the stage lighting is integrated into the reflectors. Diffusion chambers are able to adjust the amount of diffusion and absorption in the hall to suit different types of music such as jazz, rock, and classical music. The openings to the reverberation chambers are covered by small pieces of timber that are angled in order to adjust the amount of diffusion and absorption. Furthermore, curtains inside the reverberation chamber allow for more absorption and the reverberation time can be adjusted between 1.5 to 1.8 s (Olofsson, 2013, p. 29). Information about stora salen in Västerås is displayed in Table 2.4 (Olofsson, 2013, p. 28).

2.7 Statistical Analysis

For learning purposes, no statistical tools other than Excel and VBA-programming have been used during the evaluation of data in this master thesis. This section explains the basic statistics used in order to evaluate the collected data. Moreover, VBA-programs which have been written in Excel can be found in the Appendix section.

Mean

The mean is defined as "The sample mean of the variable is the sum of observed values x_1, x_2, x_3,..., x_n in a data divided by the number of observations n." The definition of the sample mean is given in equation (2.18)

Figure 2.16: Västerås' stage and audience showing the layout of furniture on the stage.

Figure 2.17: Stage in Västerås with double bass seating and timpani in front of risers where woodwind and other percussion is located.

(Isotalo, n.d., pp. 27 - 28).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{2.18}$$

Standard deviation

The standard deviation σ is a positive number which indicates variability or "a kind of average of the absolute deviations of observed values from the mean of the variable in question" (Isotalo, n.d., p. 34).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{2.19}$$

Median

The sample median is calculated by arranging the data in an ordered list. If the amount of data is an odd number, the median is the value in the middle of the data collection. If the amount of entries in the data collection is an even number, the value of the median is the value between the two middle entries in the ordered list (Isotalo, n.d., p. 26). Since the lowest and highest values are sorted out, this is a better representation of an average value of a set of data and therefore often used for statistical representation rather than an arithmetic mean.

Interquartile range

The definition of range is the difference between the maximum [Max] and minimum [Min] values in a collection of data (Isotalo, n.d., p. 29). The interquartile range [IQR] is defined as the difference between the first and third quartiles of a data collection. Quartiles also denoted Q_1, Q_2, and Q_3 is the division of data where Q_1 is the division between the first 25% and the top 75%. The second quartile is the division of the lowest and highest 50%, a.k.a. the median. The third quartile is the division between the bottom 75% and the top 25% (Isotalo, n.d., pp. 30 - 31).

Boxplot and outliers

In order to create a box plot, a five number summary is needed: Min, Q_1, Q_2, Q_3, and Max. When the variables are obtained, it is possible to make a box plot. For an example of this, see Figure 2.18. On the axis are the different categories for each box plot. In this case, the first category is OAI which stands for Overall Acoustic Impression. It is possible to see that the lowest whisker at a value of 7 represents the min value. The lower part of the "box" which is filled with an angled hatch represents the Q_1, or the first quartile or the 25-percentile. This lower part of the box extends to the Q_2, or the median, which is marked by a line and a circle with a white fill. The upper part of the box represents Q_3, or the third quartile or 75-percentile. As a coincidence of the collected data for OAI, the Q_3 and Max coincide at a value of 10. Furthermore, the REV category seems to have a somewhat strange box plot, but the explanation for this is that only the Median is plotted due to that Min, Q_1, Q_2, Q_3, and Max coincide at a value of 5.

The crosses in Figure 2.18 represent outliers in the collected data. From the collection of data, Q_1 and Q_3 are calculated in order to find the IQR. The lower limit as well as the upper limit is calculated through equations (2.20) and (2.21). If a data value is either below the lower limit or above the upper limit, it will be removed from the evaluated data. Removing data may seems unnecessary, but as seen in Figure 2.18 in the SPL category the Min value is a 5, Q_1 at 8, the median at 9, Q_3 at 10, Max at 10. One musician has rated the SPL at 0. This is clearly an outlier, which differs from the opinion from all other musicians. There could be many explanations for the answers from this particular musician; it could be misinterpretation of the rating system, problems with sound levels due to hearing issues, type of instrument in combination with location, etc. Although all this is important to consider, it must be listed as an outlier in order not to taint further calculations such as correlation. Moreover, cases such as this should be studied in order to consider the severity of the rating and find why it differs from other musicians.

$$limit_{lower} = Q1 - 1.5IQR \tag{2.20}$$

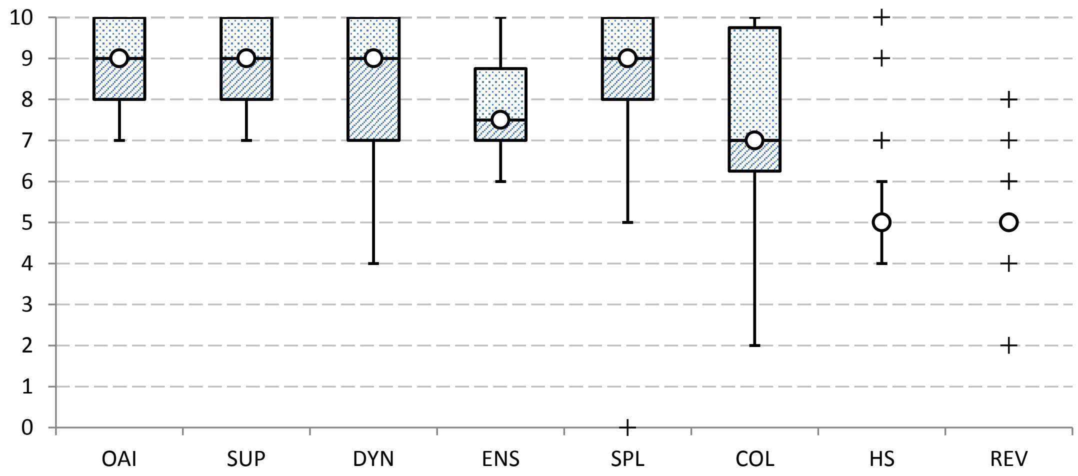

Figure 2.18: Graphical representation of Västerås musician opinions as an example of a box plot.

$$limit_{upper} = Q3 + 1.5IQR \tag{2.21}$$

2.7.1 Spearman's rank order coefficient

In order to calculate the correlation between subjective judgments and objective measures, a correlation coefficient, often denoted as r, needs to be calculated. Usually, r is calculated through the Pearsson method, but since this method works better for correlation between variables which are linear, this might not be the best choice for the study. An alternative to the Pearsson correlation coefficient is the Spearman's rank order coefficient which is often denoted ρ. In contrast to Pearsson's r, Spearman's ρ ranks the two compared variables and through the ranking determines if there is correlation. This means that monotonic relationships which might not be linear can also be detected. Nevertheless, a monotonic relationship means that as one variable increases so does the other.

As seen in Figure 2.19, the first set of data to be ranked is collected in column B(X) and the second set of data is in column C (Y). Column E and F ranks the order of column B and C respectively and are named X_{Ra} and Y_{Ra}. Values are ranked from lowest to highest with the lowest value receiving a rank of 1. If there are several values in the collected data-set which share the same value, or tie with each other, the average rank for these values is averaged. For instance in column E, rank 1 and 2 can be seen, but not three. This is because the next ranked numbers which would have been ranked as 3, 4, and 5 share the same value and therefore they all receive a 4 which is the average rank $(3 + 4 + 5)/3 = 4$.

In column H, the difference between the two ranks in column E and F are calculated $(X_{Ra} - Y_{Ra})$. The sign of the value in column H does not matter since the value is squared in column I and then used for calculating ρ. Equation (2.22) calculates ρ, but should only be used if there is an absence of ties among the ranks. In case of ties, a more complicated formula according to equation (2.23) should be used.

$$\rho = 1 - \frac{6\sum d^2}{N^3 - N} \tag{2.22}$$

Where: N is the number of data.

$$\rho = \frac{CoVar}{\sigma_{X_{Ra}} \cdot \sigma_{Y_{Ra}}} \tag{2.23}$$

Where: $\sigma_{X_{Ra}}$ and $\sigma_{Y_{Ra}}$ is the standard deviation of X_{Ra} and Y_{Ra} respectively.

$$CoVar = \frac{\sum((X_{Ra} - \bar{X}_{Ra}) \cdot (Y_{Ra} - \bar{Y}_{Ra}))}{N - 1} \tag{2.24}$$

Where: $\bar{X}_{Ra}$ and $\bar{Y}_{Ra}$ denotes the mean-value of the respective rankings.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Hall:	Vasteras													
2	Sub/Obj:	COL	ST_e												
3															
4		Values			Rank										
5	Position	X	Y		X_{Ra}	Y_{Ra}		d	d^2		X_{Ra}-M_X	Y_{Ra}-M_Y	Product Diff	N	22
6	CM	7	-10.8375		9.5	14		-4.5	20.25		-2	2.5	-5	sum	2673
7	P3	7	-9.775		9.5	20		-10.5	110.25		-2	8.5	-17	r-Spearman	-0.56
8	P1	9	-9.968125		15.5	17		-1.5	2.25		4	5.5	22		
9	S3	5	-9.266875		4	22		-18	324		-7.5	10.5	-78.75	Calc r-Spearman	
10	P3	6	-9.775		6	20		-14	196		-5.5	8.5	-46.75		
11	S1	8	-11.213125		13.5	11		2.5	6.25		2	-0.5	-1		
12	P2	10	-12.483125		19.5	7.5		12	144		8	-4	-32		
13	S2	9	-12.48375		15.5	3		12.5	156.25		4	-8.5	-34		
14	S2	10	-12.48375		19.5	3		16.5	272.25		8	-8.5	-68		
15	S2	7	-12.48375		9.5	3		6.5	42.25		-2	-8.5	17		
16	P2	10	-12.483125		19.5	7.5		12	144		8	-4	-32		
17	CM	7	-10.8375		9.5	14		-4.5	20.25		-2	2.5	-5		
18	P1	2	-9.968125		1	17		-16	256		-10.5	5.5	-57.75		
19	P3	4	-9.775		2	20		-18	324		-9.5	8.5	-80.75		
20	S1	5	-11.213125		4	11		-7	49		-7.5	-0.5	3.75		
21	S2	10	-12.48375		19.5	3		16.5	272.25		8	-8.5	-68		
22	S1	5	-11.213125		4	11		-7	49		-7.5	-0.5	3.75		
23	S2	8	-12.48375		13.5	3		10.5	110.25		2	-8.5	-17		
24	P2	7	-12.483125		9.5	7.5		2	4		-2	-4	8		
25	CM	7	-10.8375		9.5	14		-4.5	20.25		-2	2.5	-5		
26	P1	10	-9.968125		19.5	17		2.5	6.25		8	5.5	44		
27	P2	10	-12.483125		19.5	7.5		12	144		8	-4	-32		
28				Mean	11.5	11.5						Sum	-481.5		
29				Std	6.35	6.41						CoVar	-22.93		

Figure 2.19: Example of a Spearman's correlation calculation done in Excel 2010 done with Visual Basic for Applications [VBA].

As seen in Figure 2.19, there are many ties and therefore the use of equation (2.23) should be performed in this case instead of the simplified (2.22) Statistics (n.d.). Observe that if the σ in equation (2.23) approaches zero for any rankings the correlation would approach negative or positive infinity. Therefore, it is important to consider if ρ is too high due to lack of spread in data. Table 2.5 gives general guidelines to what range the absolute value of ρ signifies a monotonic relationship. There is also an example listed in the table displaying how the monotonic relationship of the correlation coefficients is emphasized in the table in the Result chapter.

Table 2.5: Guideline for monotonic relationships through the use of Spearman's correlation coefficient (Statstutor, n.d., p. 2).

Range of correlation $\lvert\rho\rvert$	monotonic relationship	Example with emphasis
0.00 to 0.19	very weak	0.07
0.20 to 0.39	weak	0.32
0.40 to 0.59	moderate	<u>0.47</u>
0.60 to 0.79	strong	**0.71**
0.80 to 1.00	very strong	<u>**0.93**</u>

3 Method

3.1 Choice of objective parameters

The choice of objective measurement parameters are as follows: G, G_{125}, LF, ST_{early}, ST_{late}, C_{80}, D_{50}, T_{30}, EDT, BR, and TR. These have been chosen due to the preliminary literature study and comparability with CATT-Acoustic. Furthermore, because a switch broke on the pre-amplifier during two of the four measurements, another pre-amplifier had to be borrowed from the concert hall, no calibration to pre and loudspeaker has been applied. Therefore, comparing Gain values among halls is not possible and G_{early} and G_{late} were not calculated.

3.2 Measurement positions

ISO 3380-1 suggests that measurements should be made on furnished stages. Although, a presence of a full symphony orchestra is ideal, the opportunity for such an occasion is rare or costly. (Gade, 2013, p. 5) It is preferable to make the measurements with furniture, such as chairs and note stands, present. Although, if a measurement is made without a specific set-up of furniture, it could arguably be more useful in order to represent a wider variety of situations. Risers should be included in the set-up due to effects caused between different paths in the orchestra.

ISO 3382-1 proposes the height or *rec* and *src* to be 1.0 m or 1.5 m. (ISO 3382-1, 2009, p. 19) Gade states that 1.0 m is preferable due to the increased attenuation caused by furniture and musicians because of the riser geometry. (Gade, 2013, p. 5) The receiver height has been chosen to lie at 1.2 m because the orchestra plane in CATT-Acoustic is modelled 1 m above the floor and the receiver is placed about 200 mm above that. Furthermore, a height of 1.2 m correlates better to the common distance between ear and floor when sitting. Support measurements have been measured with a height of 1 m as stated in ISO 3382-1.

ISO 3380-1 suggests measurements in at least three positions, but Gade recommends extending this to at least five position because modern day equipment is faster to measure with. (Gade, 2013, p. 5) The suggested positions are indicated in Table 3.1 as well as in Figure 3.1 together with location of the positions chosen for this specific study. Yet again, Gade's experience in measuring stage acoustics is valuable and the following positions as listed in Table 3.1 have been chosen in order to be able to compare different halls to each other. However, the positions for this study were changed slightly after the first measurement in Jönköping in order to compensate for the amount of answers from Brass sections which were less considered in Gade's original positions. Another approach, used by Olofsson, is to apply a rectangular grid with constant measurement positions. However, this makes it difficult to apply to different types of stages where for instance the stage might be too narrow to allow the appropriate distance between wall and measurement position as seen in Figure 3.2 and there is a lack of compatibility with various instrument sections. Furthermore, there are too many positions to measure to be able to complete within a reasonable time limit. Therefore, Gade's measurement positions are more applicable than Olofsson's. Note that the extra position X1 is located at the grey marking near S1 in Jönköping and Musikverein. In the remainder of halls, the position is located at the back by the double bass and/or brass.

Table 3.1: Measurement positions according to Gade.(Gade, 2013, p. 5)

Denotation	Location according to Gade	Location in this study
S1	soloist position	soloist and first violin
S2	between viola and celli groups	- same as Gade -
S3	position on left in the back usually clarinet	leftmost position in the back usually horns
P1	flute leader	- same as Gade -
P2	between first and second violins	- same as Gade -
P3	rightmost position in the second row of woodwinds	- same as Gade -
X1	N/A	rightmost position usually representing brass/double bass

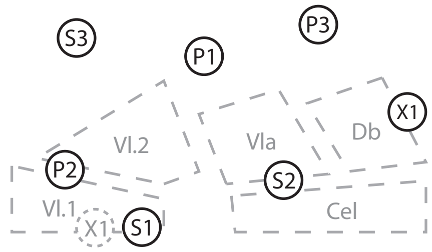

Figure 3.1: Measurement positions according to Gade with the American seating arrangement for the string section, please note that the diagram is not in scale and indication of position is found in Table 3.1. (Gade, 2013, p. 5)

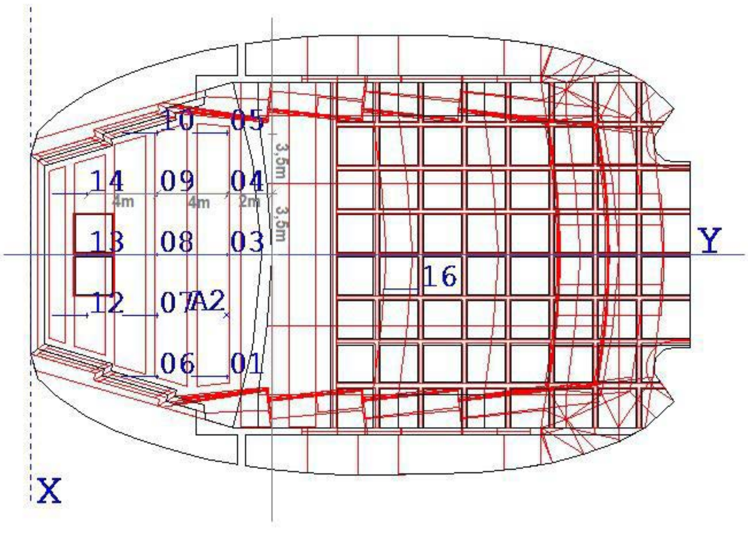

Figure 3.2: Measurement positions according to Olofsson, example is taken from the concert hall in Västerås. (Olofsson, 2013, p. 52) Scale of plan in undetermined.

For support measurements, 4 transducer positions around the source is suggested in ISO 3382-1. In 2011 Hak et al. showed that the "uncertainty in source directivity is reduced only when using 5, 7 or 8 step-wise rotations." (Wenmaekers & Hak, 2013, p. 4) However, this is not widely used.

3.3 Measurement equipment

Loudspeaker: Bruel & Kaejer OMNI 4295

Pre-amplifier: Norsonic type 280, and others borrowed from the halls

Microphone: Pearl TL-4 with omnidirectional or Figure-of-eight characteristics

Computer: Dell Studio 1747 Intel Core i7 CPU @ 1.6 GHz with Windows 7 Professional and 4 GB RAM

Sound card: D-Audio AXYS

Software: WinMLS 2004, Sketchup 8, Matlab R2013a, CATT-Acoustic v. 8.0h, Excel 2010, and Audacity 2.0.5

3.4 Calibration

Microphone

Due to the shape of the microphone it is not possible to calibrate it with a calibrator. Therefore, calibration of the microphone is done in WinMLS 2004 using the sound card by either selecting "Cal" in the toolbar or through the menu Measurement - Calibration. The in the "Level calibration" under "use input calibration" press "calibrate..." button. This opens up the new window "Input Level Calibration for Channel 1" which was adjusted for the setup.

Loudspeaker

Calibration of the loudspeaker and amplifier can be calibrated either in an anechoic- or reverberation chamber. Since Chalmers only has access to an anechoic chamber, at the department of applied acoustics in Gothenburg, the former method for calibration was chosen. In accordance to ISO 3382-1, calibration of the loudspeaker and amplifier is important for the Strength parameter G and the denominator term should have a reference distance of 10 m. However, due to the dimensions of the anechoic chamber a *src-rec* distance of 3 m was chosen since 10 m was not possible. In free-field, decreasing the distance from 10 to 3 m induces change in the reference level according to $20\log(\frac{3}{10})$, or an increase of about 10.5 dB. (ISO 3382-1, 2009, p. 13)

The paragraph above outlines how the calibration should be performed. However, in this thesis it was not possible to perform the calibration due to equipment failure during the measurements in Västerås and Gävle. The Gain switch on the loudspeaker pre-amplifier broke, resulting in a too low output for measurement. The solution to this was to borrow another amplifier from the concert hall and perform the measurements, but this made calibration impossible. An alternative could have been to return to Gothenburg, but the travelling distance was too large and re-booking was considered difficult. Since there was no point in calibrating the amplifier and loudspeaker for only two of the halls, an amplifier was borrowed in Malmö easing travels with less equipment. In turn, this makes comparisons of Strength or Gain between halls irrelevant, but the paths within a hall is still of interest.

3.5 Performance of measurement

Basic set-up:

1. Connect measurement equipment such as sound card, computer, microphone, and loudspeaker.
2. Test levels in WinMLS and adjust the gain on amplifier as well as on the input and output gain on the sound card. Warning! Do not adjust these after the measurements have started or another calibration has to be performed.

Figure 3.3: Source placed in position P2 in Västerås concerthall at a height of 1.2 m. Note tape marking on floor in order replace moved chairs and note stands.

3. Perform calibration in WinMLS.
4. Note temperature and the humidity of the air through measurements using a thermometer respectively a hygrometer.
5. Mark the measurement positions on stage with tape on the floor. It is also wise to document the layout of the stage and positions in order to replicate in the computer model.

Basic impulse response measurement for parameters such as T_{30}, EDT, G, and C_{80}[1]:

1. Place the loudspeaker in the indicated position at a height of 1.2 m.
2. Place the microphone in the indicated position with the microphone switched to an omni-directional characteristic at a height of 1.2 m.
3. Make measurement with a single sweep and check the accuracy of the measurement. Save the data in the following format SRC#_REC#
4. Repeat step 1 to 3 for all indicated positions.

Basic measurement for ST:

1. Place the loudspeaker in the indicated position 1 m above the floor and please remember to clear anything at a radius of 2 m from the acoustic center of the source.
2. Place the microphone in one of the four indicated position at a distance of 1 m from the loudspeaker. Switch the microphone to an omni-directional characteristic and make sure it is placed 1 m above the floor. For the transducer it is also suggested that all furniture is moved as a distance 2 m from the acoustic center of the microphone in accordance with ISO 3382-1.

[1]Measurements were performed with a figure-of-eight microphone for step 2 for LF in accordance with ISO 3382-1.

3. Make measurement with a single sweep and check the accuracy of the measurement. Save the data in the following format SRC#_REC# where the receiver is 1 to 4 due to the four positions taken around the loudspeaker. Perform the impulse response measurement for all four microphone positions with the loudspeaker placement the same position.

4. Repeat step 1 to 3 for all indicated loudspeaker positions.

3.6 Survey

Since this is a continuation of Olofsson's thesis in 2013, the survey has already been designed and sent to the orchestras. Therefore, it is not possible to change the parameters in the survey, only reminders of response were organized. The survey for Gävle's symphony orchestra has been attached in Appendix A.

The symphony orchestra's musicians were asked to rate their respective home venue. According to Dammerud home venues should be excluded from the survey and only halls which the musicians regularly play in should be included. He argues that there could be a lack of judgment otherwise "due to limited experience or adaptation to certain acoustic conditions" (Dammerud et al., 2010, p. 2). Nevertheless, the proposed master thesis included surveys from the musicians home venues and the author is through Dammerud's insight aware that the judgment of the musician might be biased. The surveys are conducted in Swedish due to the majority in nationality of the musicians in the orchestras of the concert halls. Simplified translations of the survey in found in Appendix A Table A.1.

3.7 Computer models

Models were built in Sketch-Up [SU] by Mats Olsson at Akustikon/Norconsult and edited by the author in Sketchup 8. Acoustic calculations were performed in CATT-Acoustic, which in the "Full detailed calculation", predicts through a Randomized-Tail-corrected Cone-tracing [RTC]. RTC is based of Dalenbäck's experience with Image Source Method [ISM], ray-tracing, and combinations of the two. Dalenbäck (n.d.).

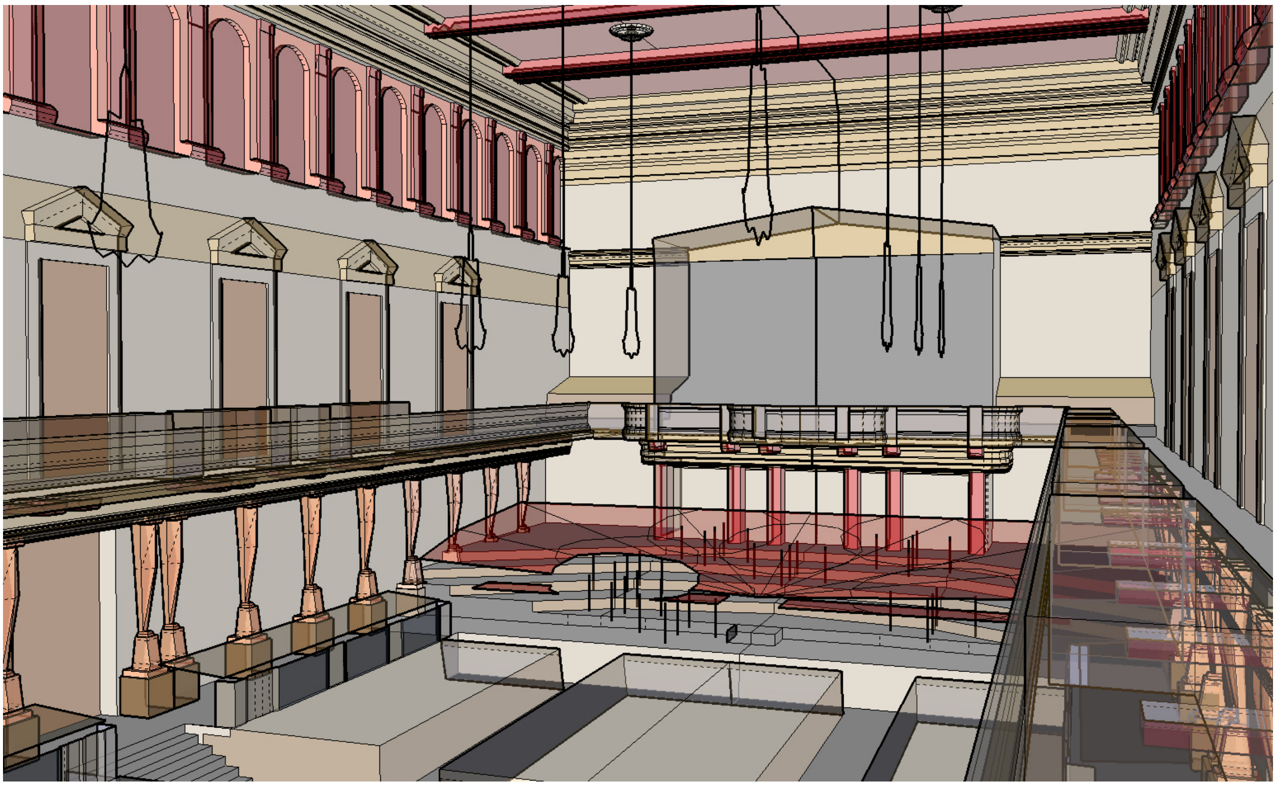

Figure 3.4: VM CATT-Acoustic model showing stage with cuts for support measurements.

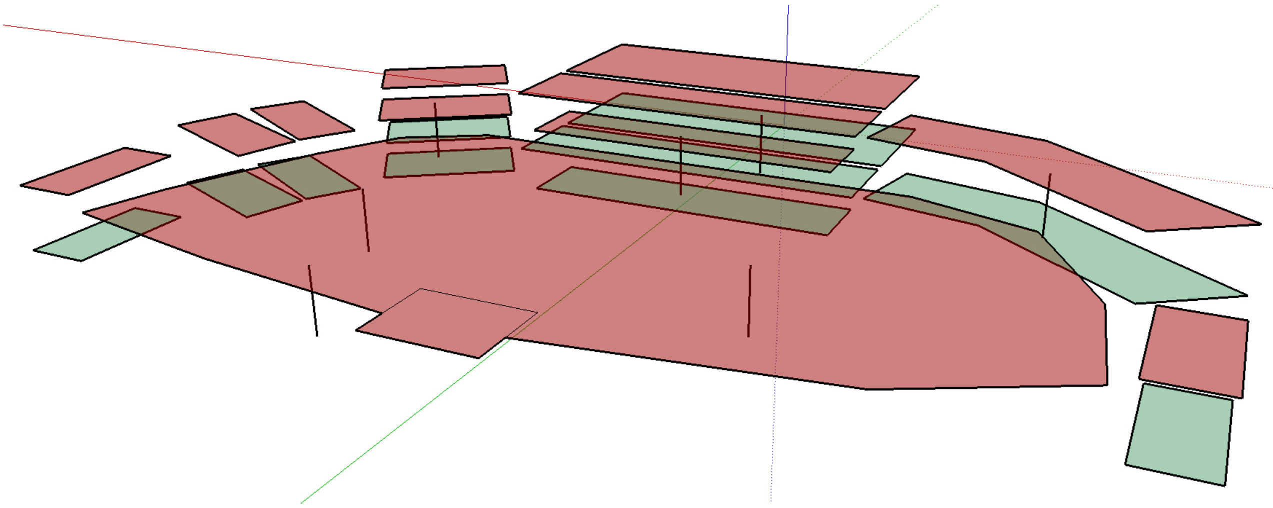

Figure 3.5: Orchestra layout in SKP for Gävle's concert hall. The green surfaces are risers and the red is the actual orchestra absorption which is placed 1 m above the floor or riser.

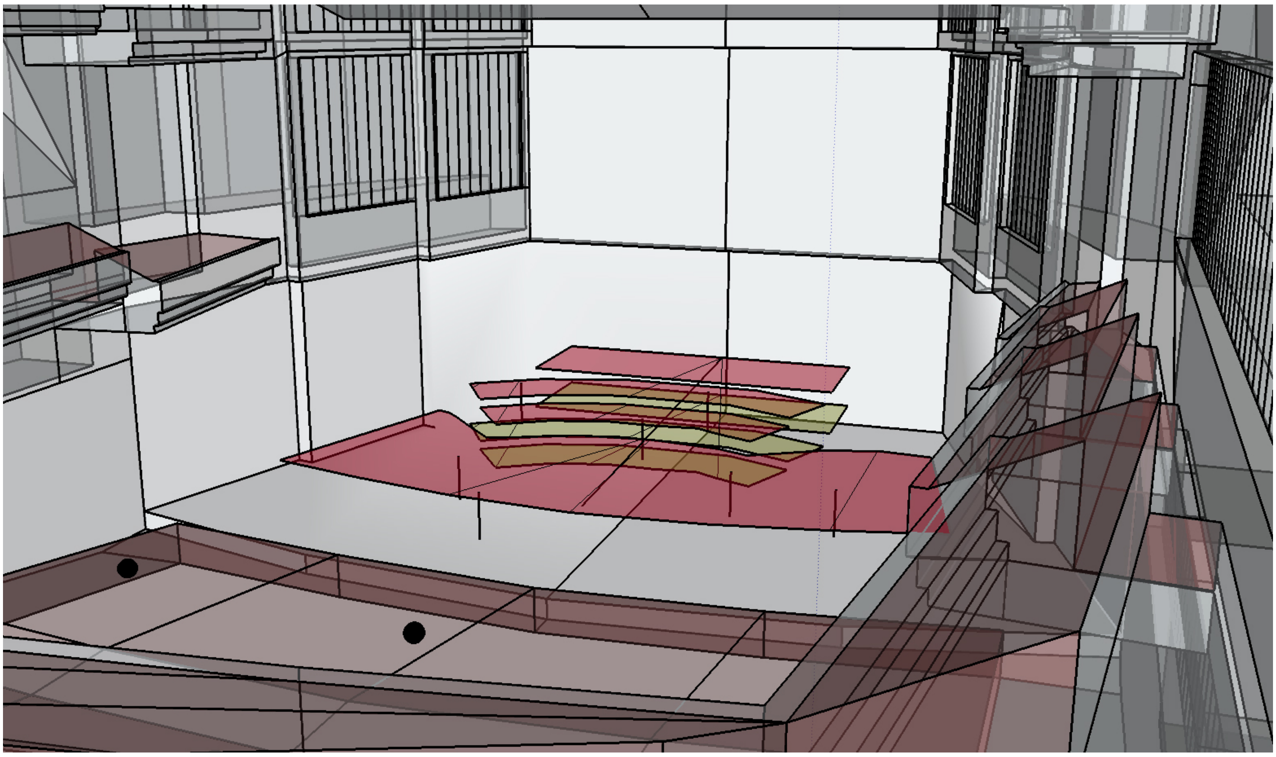

Figure 3.6: VST CATT-Acoustic model which is a WRL file exported from CATT-Acoustic to Sketch-Up where the orchestra is modelled.

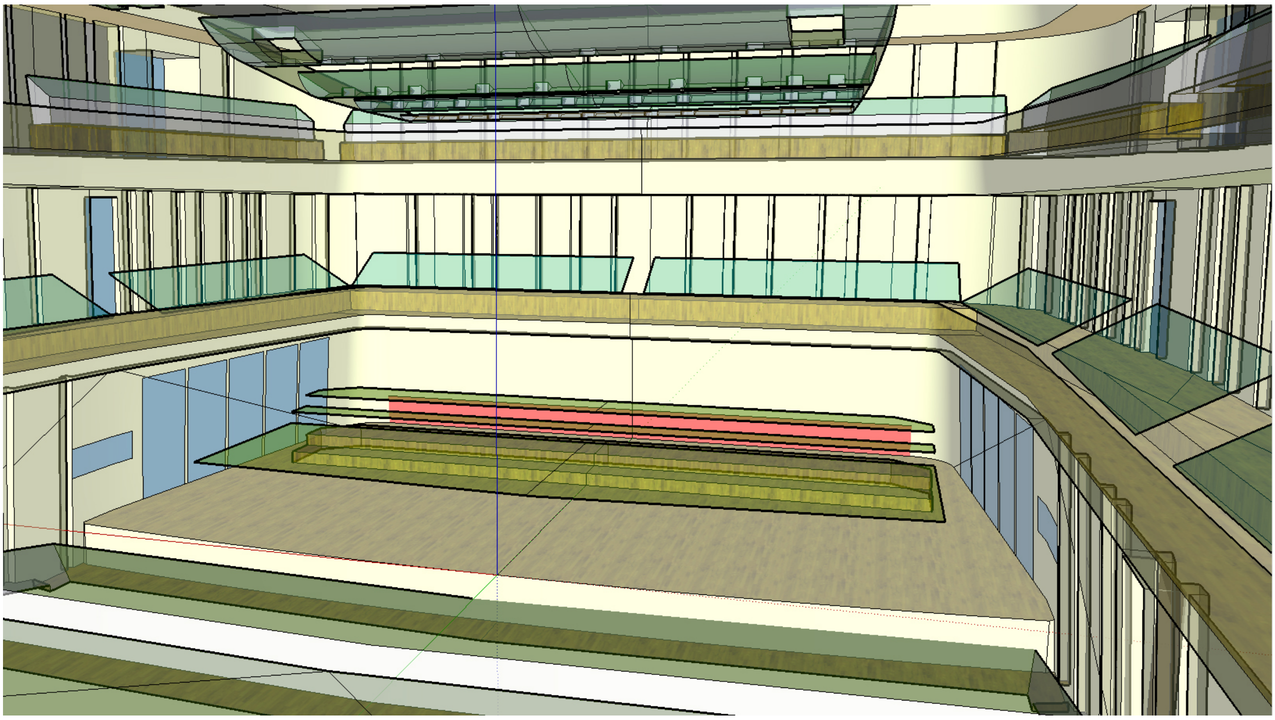

Figure 3.7: JKPG SKP model which is imported into CATT-Acoustic.

The amount of rays according to the CATT-Acoustic manual should be at least 5000. However, the size of concert hall models are quite large and therefore the number of rays per octave was set to 100 000 as a standard, and VM where calculated with 1 000 000 rays per octave. The first generated a calculation time of about 5 hours, while the second generated calculation of about 15 hours for the VM-model. Since there was no significant differences in the results 100 000 rays per octave was used in CATT-Acoustic for the final calculations.

Truncation time should be set to be longer than the T_{30} value in order to not cut the reverberation tail. For a concert hall, the truncation time might lie in around 3000 ms due to that some octave bands might have an extended reverberation. Absorption data for the VM-model is displayed in Table D.1 and other halls could have different data depending on material qualities. The orchestra plane is located at a height of 1 m above the floor which is implemented in the later. Earlier models used an orchestra plane 1.2 m above the floor and has been changed to a level of 1 m. In the CATT-Acoustic model, the source at each positions is set to white noise at 94 dB.

4 Result and discussion

4.1 Subjective judgment

This section covers the collected subjective data with an overview and then details for each hall. In order to make tables and figures more comprehensive, certain abbreviations have been used throughout this thesis, see Table 4.1 and 4.2.

Table 4.1: Instrument abbreviations used in this thesis.

Instrument	Abbreviation
Bassoon	Ba
Cello	Cel
Clarinet	Cl
Double Bass	Db
Flute or Piccolo	Fl
Harp	Hrp
Horn	Hrn
Oboe	Ob
Percussion	Perc
Trombone	Trb
Trumpet	Trp
Tuba	Tub
Viola	Vla
Violin	Vl

Table 4.2: Survey question and their respective abbreviation as well as the meaning of minimum and maximum value.

Survey question	Abbreviation	Minimum (0)	Maximum (10)
Overall acoustic impression	OAI	Bad	Good
Room's support	SUP	Bad support	Good support
Hall's dynamics	DYN	Small	Large
Feeling of ensemble	ENS	Bad	Good
Sound Pressure Level	SPL	Bothersome	Adequate
Tone coloration	COL	Colored	Neutral
Ability to hear oneself	HS	Too little	Too much
Reverberation	REV	Too dry	Too reverberant

Table 4.3 states the response rate for each hall including the total amount of musicians in each orchestra and number of participants. Generally, the response rate is quite low and several attempts have been made to collect more opinions which has been proven difficult. In some cases, some participants have also handed in more than one survey. Duplicates have been removed and the latest version from each participant has been used. Arguably, the low participation might suggest that people with a certain opinion might have taken the survey to get their point across.

In Table 4.4 the first quartile figures are shown for the four halls included in the musician survey. Furthermore, a graphical representation for each hall is found later in this chapter in the corresponding hall section. REV is one of a subjective parameter which has the lowest standard deviation for all the halls, this observation may tell us that it is difficult to judge the REV in different positions in the halls. It is also important to note the low σ for Malmö's subjective parameters in the OAI to COL row. Furthermore, Malmö also has the lowest mean value of the Q_1 which supports the low ranking of the hall.

The median or Q_2 for all music venues is shown in Table 4.5. Malmö receives the lowest marks out of all the halls with a low mean value in categories OAI to COL of 3.2. Moreover, HS received a mean value of 3.0

Table 4.3: Response rate as well as the number of participants out of the total number of musicians in the orchestra.

	Frequency			
Instrument	GV	JKPG	VST	MÖ-C
Ba	0	0	1	2
Cel	1	2	1	5
Cl	0	1	1	2
Db	2	1	2	4
Fl	1	0	0	3
Hrn	3	3	1	1
Hrp	0	0	0	1
Ob	1	1	2	1
Perc	2	1	1	1
Trb	3	1	0	2
Trp	1	0	2	3
Tub	1	1	0	1
Vla	3	1	5	4
Vl	3	6	6	11
Participants	21	18	22	41
Orchestra members	47	31	31	90
Response rate [%]	44.7	58.1	71.0	45.6

Table 4.4: Q_1 of subjective parameters for the different halls with calculations of mean and standard deviation (σ). Note that SubPar is an abbreviation of Subjective parameters.

	SubPar								SubPar			
Halls	OAI	SUP	DYN	ENS	SPL	COL	Mean	σ	HS	REV	Mean	σ
Gävle [GV]	7.0	7.0	6.0	3.0	3.0	5.0	5.2	1.8	5.0	5.0	5.0	0.0
Jönköping [JKPG]	9.0	8.0	9.0	7.0	8.0	6.0	7.8	1.2	5.0	5.0	5.0	0.0
Malmö [MÖ-C]	2.0	2.0	3.0	1.0	1.0	3.0	2.0	0.9	2.0	4.0	3.0	1.4
Västerås [VST]	8.0	8.0	7.0	7.0	8.0	6.3	7.4	0.7	5.0	5.0	5.0	0.0
Mean	6.5	6.3	6.3	4.5	5.0	5.1			4.3	4.8		
σ	3.1	2.9	2.5	3.0	3.6	1.5			1.5	0.5		

Table 4.5: Median of subjective parameters for the different halls with calculations of mean and σ.

	SubPar								SubPar			
Halls	OAI	SUP	DYN	ENS	SPL	COL	Mean	σ	HS	REV	Mean	σ
Gävle	7.0	7.0	7.0	5.0	5.0	6.0	6.2	1.0	5.0	5.0	5.0	0.0
Jönköping	9.5	9.0	9.0	7.0	9.0	8.0	8.6	0.9	5.0	5.5	5.3	0.4
Malmö	3.0	3.0	5.0	2.0	2.0	4.0	3.2	1.2	3.0	5.0	4.0	1.4
Västerås	9.0	9.0	9.0	7.5	9.0	7.0	8.4	0.9	5.0	5.0	5.0	0.0
Mean	7.1	7.0	7.5	5.4	6.3	6.3			4.5	5.1		
σ	3.0	2.8	1.9	2.5	3.4	1.7			1.0	0.3		

which is low in comparison to the other hall which all have mean values of 5.0. Jönköping and Västerås are closely similar in the rank with a few minor differences in the mean values.

Table 4.6: Q_3 of subjective parameters for the different halls with calculations of mean and σ.

	SubPar								SubPar			
Halls	OAI	SUP	DYN	ENS	SPL	COL	Mean	σ	HS	REV	Mean	σ
Gävle	7.0	7.0	8.0	6.8	8.0	8.0	7.5	0.6	5.0	6.0	5.5	0.7
Jönköping	10.0	10.0	10.0	9.0	10.0	9.5	9.8	0.4	5.0	6.0	5.5	0.7
Malmö	4.0	5.0	8.0	2.5	3.0	5.0	4.6	2.0	5.0	7.0	6.0	1.4
Västerås	10.0	10.0	10.0	8.8	10.0	9.8	9.8	0.5	5.0	5.0	5.0	0.0
Mean	7.8	8.0	9.0	6.8	7.8	8.1			5.0	6.0		
σ	2.9	2.4	1.2	3.0	3.3	2.2			0.0	0.8		

Finally, Table 4.6 shows the third quartile values. Västerås has a slightly better value than that of Jönköping due to that HS and REV received a more optimal value of 5.0 instead of 5.5. Malmö's mean value for the OAI to COL category is a low 4.6 which is extremely low for the division between the lowest 75-percentile and top 25-percentile.

4.1.1 Jönköping

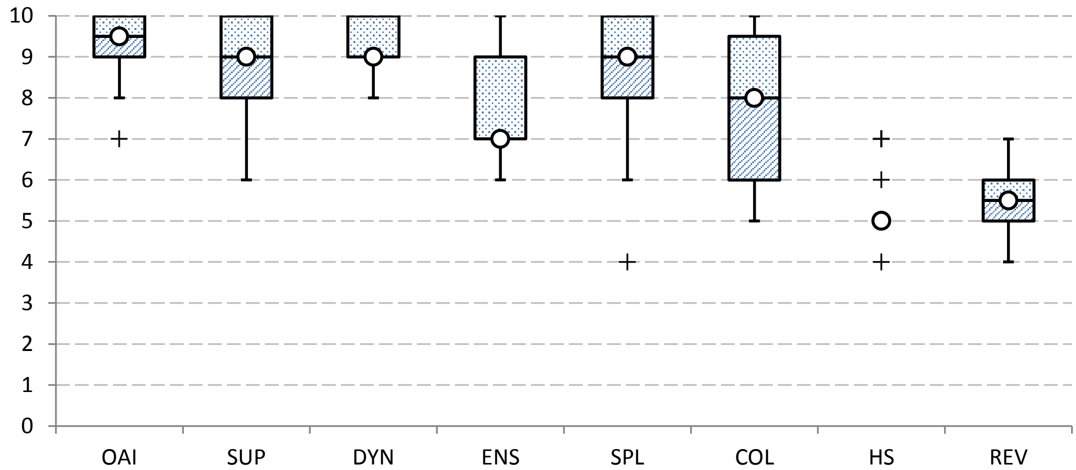

Figure 4.1: Jönköping's musicians opinions from survey.

In Jönköping, the subjective judgment is generally rated high according to Figure 4.1. OAI, SUP, SPL, and REV have an almost symmetrical distribution (bell-shaped) of rankings with the median located at the center of the box. However, the whiskers for the Max and Min value are different for OAI, SUP, and SPL where the Max coincides with Q_3. The only perfect bell shape is found in REV. This might be due to that the RT values are similar and there are no audible differences over the positions, only the judgments vary. This is further supported by the result for T_{30} listed in Table 4.21 where the σ for RT in the different halls are extremely low. In turn, this proves that the differences are small and therefore it may not be possible to hear any difference. ISO 3382 states that the just noticeable difference of EDT is 5% and if this is applied to RT, this margin would yield a JND of 0.1 s. This is quite large compared to the difference in the various positions. The RT may also vary with amounts of audience and it may change during repetition. Consequently, RT in positions on the stage may not be a preferred measurement for acoustics on concert hall stages.

Nonetheless, in Figure 4.1 DYN and ENS are skewed to the left where the Q_1 and median coincide. DYN is considered large with most values between 9 and 10. However, the skewness emphasizes that most participant agree to a value of 9 rather than 10. Furthermore, the left skewed ENS also indicates that most perceive the ensemble conditions to be good at values between 7 and 9, but that more participants agree to a value of 7.

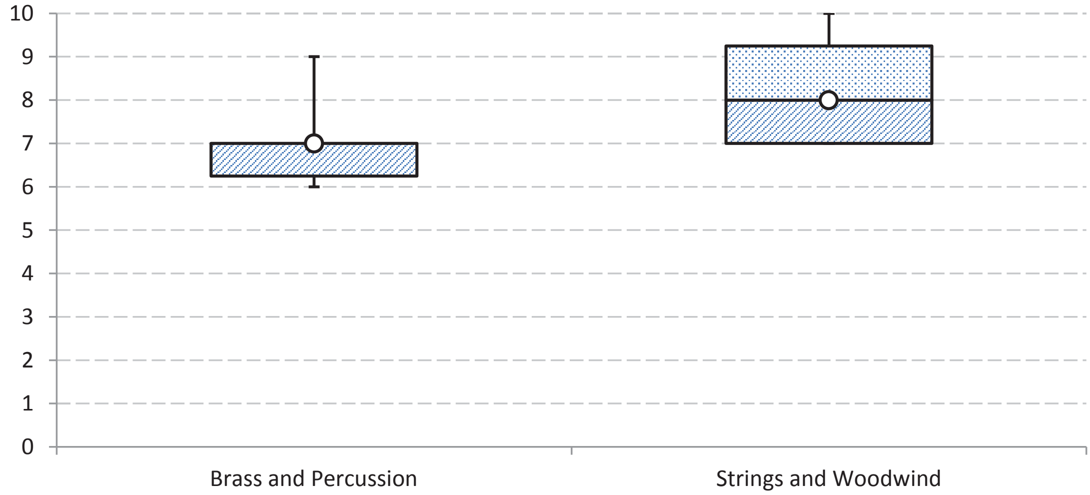

Figure 4.2: The subjective parameter ENS studied in terms of brass and percussion versus strings and woodwind.

Figure shows a further study of ENS and that brass and percussion have given a lower value between 6 and 7 for the most part. However, strings and woodwind have a higher rating of the ensemble conditions with a median at 8 and most distribution between 7 and 9.25.

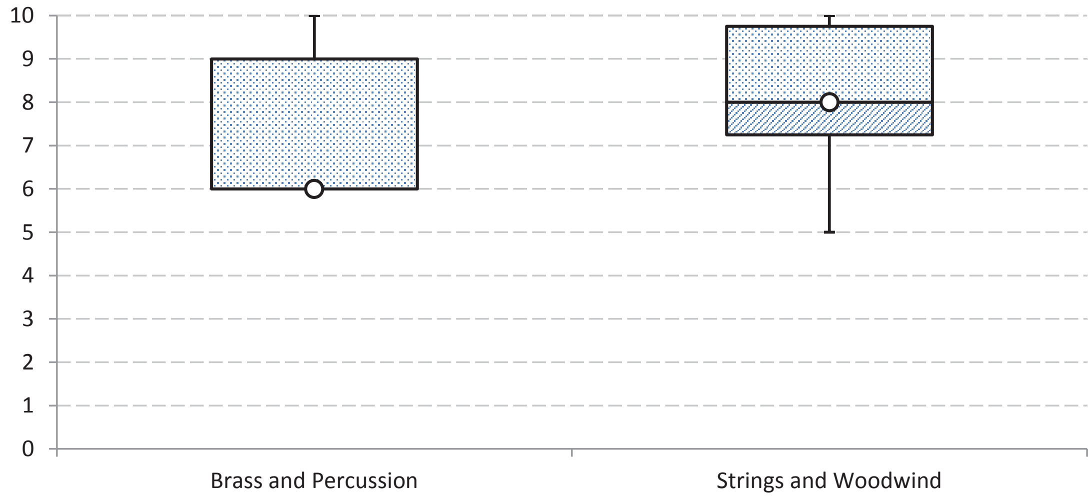

Figure 4.3: The subjective parameter COL studied in terms of brass and percussion versus strings and woodwind.

COL has the largest distribution which is quite uniformly distributed; however, the median is not located at the center of the box which means that the opinion is slightly skewed to the right. Moreover, COL is the attribute which has the largest range from 5 to 10. This makes it interesting to study in different instrumental groups in order to identify if there is a particular group which has a uniform opinion of the hall's coloration. Due to the small amount of participants in Jönköping, the COL parameter is studied only in the groups of brass and percussion versus strings and woodwind as seen in Figure 4.3. The study clearly states that brass and percussion has a mean value of 6 for COL which coincides with Q_1 and the Min-value. This would indicate that the sound is slightly colored and considered more colored in the brass and percussion section than in strings and woodwind. However, Table 4.7 displays that 61.1 percent perceive the COL to be neutral. This includes several horn players and one tuba while one trombone perceives the sound as sharp and one Perc did not yield an answer. It is evident that the lack of participants make evaluations of the acoustics difficult in more detailed groups. On the other hand, most of the brass and percussion section do find the result slightly colored to neutral and this coincides with the identification of color distribution.

Table 4.7: *Jönköping concert hall and the coloration as indicated by COL and answer to *).*

Color	Number of musicians	Percent	Instruments
Dark	0	0	-
Neutral	11	61.1	3 Hrn, 3 Vl, 2 Cel, Cl, Tub, Vla
Sharp	3	16.7	Db, Ob, Trb
No Answer	4	22.2	3 Vl, Perc

4.1.2 Västerås

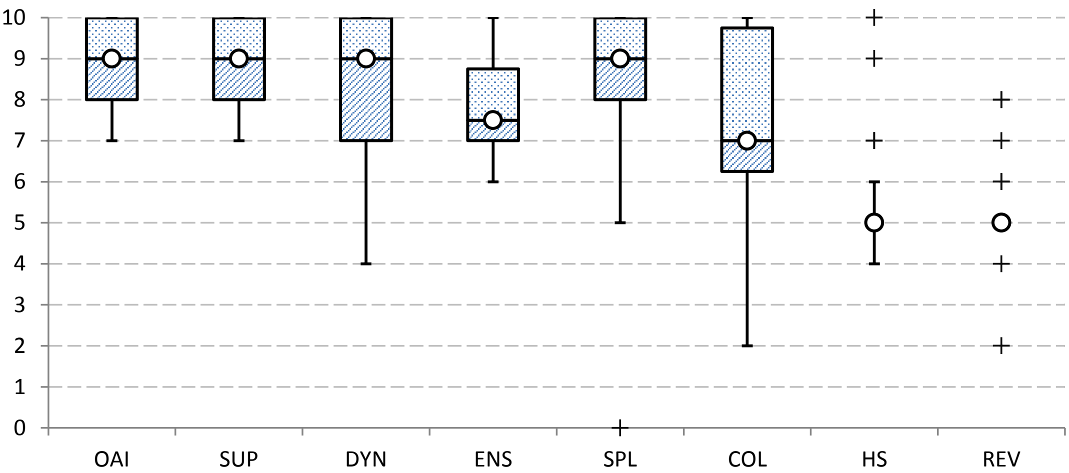

Figure 4.4: Västerås musicians opinions from survey.

In Västerås, OAI seems to be rated very high at a median value of 9 and most of the musicians agree on this since Q_1 and Q_3 varies between 8 and 10. Likewise, the SUP has exactly the same distribution as OAI. SPL, is also given the same rating by the musicians except that the minimum value is slightly lower at a rating of 5 in comparison to OAI and SUP which has a Min value of 7.

Moreover, in Figure 4.4 DYN represents a wide variety in the judgment of the dynamics. Carl Petersson, a pianist who has played both with an orchestra and solo in Västerås, shares his acoustic impression of the concert hall as being one of the better halls in Sweden. He goes on to say that in terms of acoustics this particular stage strongly conveys the sense that the audience fully perceived what the performer does.[1] Furthermore, Petersson enlightens us on his perception of the Västerås' lack of intimacy: "Våsterås does not feel intimate. It feels more like a large international hall which is strange because it is medium sized - smaller than Gothenburg yet it feels more grandiose due to the balconies. In turn, this might be the reason for straining a bit harder while playing."[2] This statement could partly support the varied perception of dynamic range in the hall which might be due to perception on intimacy and straining while playing. In addition, the comment displays the effect of visual aspects in the hall and how details such as balconies can influence the intimacy of the hall.

COL has the widest distribution of ratings which varies from a minimum value of 2 at lowest (note that this is not an outlier). Q_1 is 6.25 while the median is at 7, Q_3 is 9.75, and Max is 10. A lower value of COL indicates that the sound is colored, while a higher value indicates that the sound in neutral. Therefore, the musician perceive the Västerås concert hall somewhere between neutral and slightly colored. Table 4.8 states what coloration of the sound as perceived by the participants. If there was no indication whether the coloration is dark, sharp or neutral in the survey and the rating at COL was 7 or higher, the musician has been recorded as neutral in Table 4.8. This has been applied throughout the thesis.

[1] Original response in Swedish: Jag tycker att Västerås konserthus är en väldigt bra lokal. En av de bättre i Sverige. Helt klart. Akustiskt känner man att det man gör kommer ut och att publiken hör det man gör. (Petersson, 2014) Text paraphrased by author.

[2] Original response in Swedish: Västerås känns inte så intimt. Det känns mer som en internationell stor sal vilket är konstigt för att den är medelstor - mindre än Göteborg men känns mer grandios på grund av balkongerna. Detta i sig gör att man kanske tar i lite mer när man spelar. (Petersson, 2014) Text translated by author.

Table 4.8: *Västerås concert hall and the coloration as indicated by COL and answer to *).*

Color	Number of musicians	Percent	Instruments
Dark	2	9.1	Cl, Ob
Neutral	15	68.2	4 Vl, 3 Vla, 2 Trp, Ba, Hrn, Perc, Db, Cel, Ob
Sharp	5	22.7	2 Vl, 2 Vla, Db
No Answer	0	0	-

The survey which is made prior to this master thesis and had already been sent to orchestras and therefore no changes could be applied. In the survey, *) is supposed to be related to the coloration of timbre and asks: "Is the timbre of the orchestra dark (too much bass), hard/sharp or neutral?". The participants have a choice to answer yes or no to this question. Most likely, the coloration fits into one of the three categories; however, the choice of yes/no seems quite confusing. This is supported by participants rating a 9 which would indicate neutral, but answering "no" indicating that neutral is not correct to describe the timbre. Furthermore, below the previous question, the survey asks: If yes, in that case what? An alternative solution is to make the survey simpler by just presenting the three coloration of timbre and allowing the participant to circle the indicated choice and maybe complementing "dark", "neutral", and "sharp" with "other".

In addition to the confusing coloration question, another type of scale could have been chosen for the bipolar scales. In OAI for example, one extreme goes from "bad" to "good". SPL and COL however have a different scale from "disturbing" to "sufficient" and "colored" to "neutral". Commonly, a Likert scale could have been applied, e.g. OAI could have been stated as "The total acoustic experience is great" then the scale could go from "Strongly Disagree" to "Strongly Agree". For COL, the statement could be: "The coloration of the timbre is neutral" and the scale from "Strongly Disagree" to "Strongly Agree" in order to eliminate confusion between many different scales and what is stated as extremes on the bipolar scales. Furthermore, a Likert scale usually has five different levels of a agreement which would have the participants fill in the survey quicker than on a scale from 0 to 10, which takes more effort to be precise.

Since COL is the Subjective parameter which varies the most in Västerås, and as indicated above this can be due to the confusing survey design. However, Table 4.8 states that about 68.2 percent of the participants believe the sound to be neutral while only 9.1 percent think the sound is dark and 22.7 percent think the coloration is sharp. Sharpness, is according to two Vl is due to the sharpness from the violins, Vla do not indicate what is sharp, and Db says that the sharpness is caused by woodwinds. However, the woodwinds (Cl and Ob) rate the coloration as "dark", but with a scale in COL of 9 which would indicate neutral.

4.1.3 Gävle

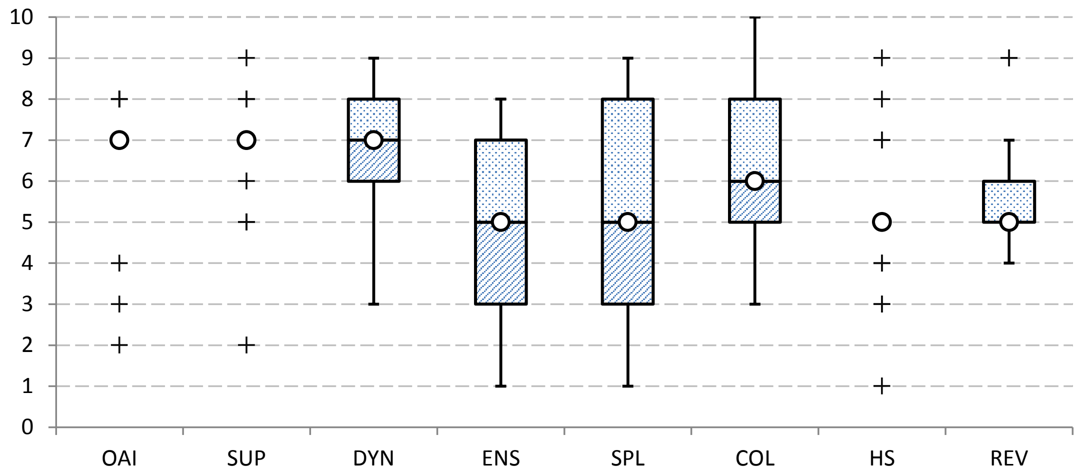

Figure 4.5: Gävle's survey result for explored subjective parameters.

In contrast to Jönköping and Västerås, Gävle's coloration of timbre was only classified as "neutral" by 33.3

*Table 4.9: Gävle concert hall and the coloration as indicated by COL and answer to *).*

Color	Number of musicians	Percent	Instruments
Dark	1	4.75	Trb
Neutral	7	33.3	2 Vla, Cel, Fl, Ob, Trb, Vl
Sharp	6	28.6	Vla, Tub, Perc, Hrn, Vl, Db
No Answer	6	28.6	2 Hrn, Trp, Perc, Db, Vl
Lack of middle	1	4.75	Trb

%, but still the most frequent choice of the participants. "Neutral" was often chosen by string and woodwind instruments with the exception of one Trb. The "neutral" coloration is closely followed by "sharp" and "no answer" both with a percentage of 28.6 in contrast to only 4.75 % indicating "dark" color. Since a staggering 28.6 % gave "no answer", this was investigated through comments of the participants: "It is difficult to assess, even if I only move half a meter, it changes a lot" and this could be the explanation why so many did not give an answer. Another explanation might lie in one answer which indicated that there is a "lack of mid-frequencies", it is possible that the other musicians agree with this statement and did therefore not answer any of the given alternatives. Both theories are supported by that most of the people who did not reply about type of coloration also gave a lower score on COL, which would indicate that the sound is colored but did not fit any of the given coloration alternatives. This could be an indication that the color questions are oversimplified.

4.1.4 Malmö

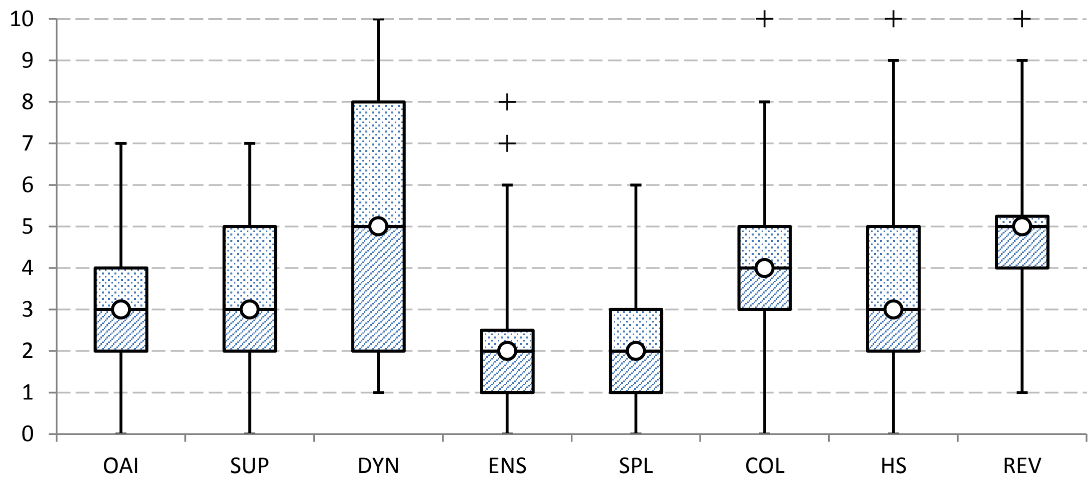

Figure 4.6: Malmö musicians opinions from survey.

As seen in Figure 4.6, Malmö is generally ranked the lowest of all four concert halls in this study with medians for ENS and SPL at a low value of two. This could be explained by that the orchestra is moving to a new concert house in about a year and therefore do no longer enjoy the environment that they are in.

The stage is slightly larger and is an agreeable size in comparison to Barron limits, yet with the full symphony orchestra, consisting of 90 musicians, the stage feels crowded in comparison to other stages in this study. It was also observed during the measurements that musicians were tightly placed next to each other restricting a comfortable zone to perform in. During a tour of the current concert house, Mikael Derving pointed out the lack of practice spaces and limitations in changing rooms. These facilities, or lack there of, may also influence the ranking of the subjective opinions in the concert hall. It was also observed that due to the lack of practice spaces in other parts of the building, more musicians, such as wood wind and string instruments, stayed in the large concert hall after the orchestra rehearsal. Of course, practising with several different people at the same time and not having a personal space could also affect the scores in the survey.

The range of the different values seem to be large in Malmö with participants' grades ranging from 0 to 10, see Figure 4.6. However, the DYN category is especially interesting because it has a Q_1 of 2 and a Q_3

value of 8. In a conversation with Jan-Inge Gustafsson at Norconsult, it was discussed why the dynamics in Malmö is so varied while other subjective parameters seem to have a more constricted distribution. Jan-Inge defines dynamics as the ability to create a nuance from pianissimo to fortissimo. However, the definition to this may vary among musicians and therefore the subjective grading of DYN may also be affected by the lack of a unified definition. However, other halls do have a more narrow distribution and it may actually be a tendency in Malmö's old hall for varied dynamics at different parts of the stage.

DYN is more closely studied for different instruments as well as sections of the orchestra in Figure 4.7. Vla is responsible for low values on the DYN with a median of 2. There are also some Vla which do rate the DYN as a 10, but this is less common with a Q_3 of 4. The reason for this may lie in the Viola itself because it is an instrument which does not particularly stand out and a dynamic range might be difficult to achieve. Moreover, the placement of Vla is usually on the right hand side of the conductor in the middle which means that the directivity of the instrument does not contribute to the instrument reaching the audience in front. In contrast, the first violins (Vl1) are usually placed at the left hand side of the conductor which means that the first violins have an easier time contributing to the dynamics in the audience and therefore have a greater dynamic range. Vl rate the DYN with a median of 7 which shows inconsistencies within the string section for the dynamics. Db seems to have an even greater range with values between 2 and 9. Cel, like Db, has a wide range of the DYN which must mean that there is great variation depending on the location on stage. Brass and percussion were displayed in one category due to the lack of numerous participants playing the various instruments. It is observed that they rate the DYN low with some exceptions rating the DYN high. Woodwinds have a slightly higher judgment of DYN compared to the brass and percussion section.

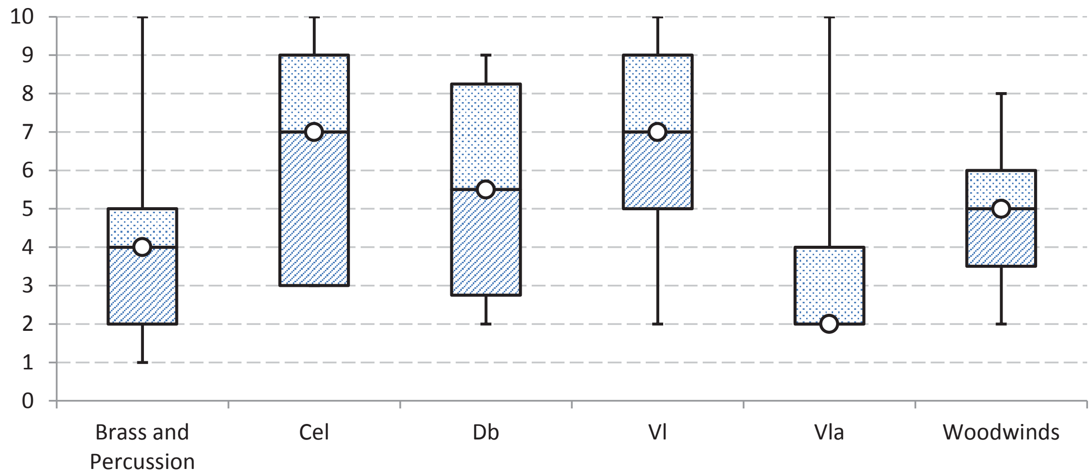

Figure 4.7: Study of DYN distribution among instruments and instrument sections.

COL in Malmö has more consistent values among the participants for Q_1 and Q_3 as seen in Figure4.6 than other halls. However, Min and Max values have a wide range which is consistent with other subjective values in the Malmö concert hall. In contrast to other halls included in the survey, Malmö's coloration is mostly considered to be "sharp" with a percentage of 57.3 % according to Table 4.10. "Sharp" coloration is acknowledged by various instruments sections. "No answer" follows "sharp" with 19.5 % and mostly woodwind, percussion, and few strings have listed this as coloration of the timbre. However, no instrument in the brass section has listed "no answer". On the other hand, "dark" seems to be applicable to both brass which consists of Trp and Hrn as well as string instruments such as Db, Cel, and Vl. "Neutral" has only been mentioned by 7.3 % of the participants and correlates well to the low score for the COL category.

HS

When comparing all the subjective values collected from the four halls, HS seems to be the parameter with the smallest spread. Arguably, hearing oneself may not be difficult to achieve although there are many outliers. Jönköping has four musicians which answered that they hear themselves too much Perc, Vl, Hrn, and Cel, while one Vla answered too little. On the other hand, Västerås has four musicians Hrn, Trp, Vla, and Vl that all answer that they hear themselves too much and values range from 7 to 10. This may indicate that there

*Table 4.10: Malmö concert hall and the coloration as indicated by COL and answer to *).*

Color	Number of musicians	Percent	Instruments
Dark	6.5	15.9	2 Db, 2 Trp, Cel, Vl, 0.5 Hrn
Neutral	3	7.3	Cel, Fl, Vl
Sharp	23.5	57.3	7 Vl, 3 Cel, 3 Vla, 2 Db, 2 Trb, Ba, Cl, Fl, Ob, Trp, Tub, 0.5 Hrn
No Answer	8	19.5	2 Vl, Ba, Cl, Fl, Hrp, Per, Vla

is a problem in certain positions. In Gävle, outliers for HS vary wildly with Perc, Trb, Hrn, and Db hearing themselves too much and Hrn, Vl, and Db hearing themselves too little. As seen in this example, the judgment seems to vary even within the same instrument group.

4.2 Objective parameters

This section presents objective parameters which includes both measurements and calculations. Note that all positions are on stage and not in the audience. Therefore, values may differ from the optimal values which are usually for positions in the audience. The reverberation time is a prime example of shorter values on stage than that of the audience. In Table 4.11, mean values for all the hall measurements are displayed for a quick overview of the similarities and differences. The mean values of calculations in the halls are displayed in Table 4.12.

Table 4.11: Collection of objective measurements (not calculations) with averages from all halls. Note that Malmö is the current hall.

Halls	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
Gävle [GV]	1.90	1.82	3.06	57.4	12.9	0.31	-10.8	-13.5	17.6	1.14	0.76
Jönköping [JKPG]	2.02	1.91	0.11	51.0	18.6	0.48	-12.2	-15.7	19.4	1.02	0.78
Malmö [MÖ-C]	2.00	1.70	2.40	49.9	11.6	0.57	-12.9	-14.5	14.9	1.20	0.78
Västerås [VST]	1.72	1.62	2.28	50.2	13.6	0.15	-10.9	-13.0	17.8	1.08	0.83

Note that G is uncalibrated due to that the amplifier gain switch broke during the trip and an amplifier had to be borrowed at the hall. Therefore, it was not possible to calibrate the loudspeaker and amplifier in the anechoic chamber at Chalmers. As a result, there is not much point in comparing the G between halls; however, the individual paths between instruments within the orchestra is interesting and is further studied in subsection 4.2.3.

Table 4.12: Collection of objective calculations with averages from all halls.

Halls	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
Gävle [GV]	1.96	1.63	4.52	64.3	9.9	18.4	-13.8	-13.5	11.4	1.32	0.90
Jönköping [JKPG]	1.86	1.34	6.28	71.7	11.8	13.1	-13.2	-14.5	12.8	1.09	0.86
Malmö [MÖ-N]	2.09	1.42	6.82	73.6	9.3	14.4	N/A	N/A	10.4	1.09	0.87
Västerås [VST]	1.75	1.55	5.40	67.5	10.0	15.7	-12.7	-15.2	11.2	1.16	0.92
Musikverein [MV]	2.03	1.26	6.15	70.3	10.7	16.2	-11.3	-15.4	11.8	1.10	0.78

Figures 4.8 and 4.9 display the mean values of objective measurements and calculations respectively. The difference between the EDT for measurements and calculations are dramatic with the calculations having much shorter values. The reason for this is that there is a lack of absorption in the measurements with both the audience's as well as the orchestra's absence.

The measured and calculated clarity is displayed in Figures 4.10 and 4.11. Here the difference between measured and calculated values are extreme, especially for Jönköping which has a difference of about 5 dB. As for the calculations, Gävle seems to have the lowest value while Malmö is the highest. Since these two halls

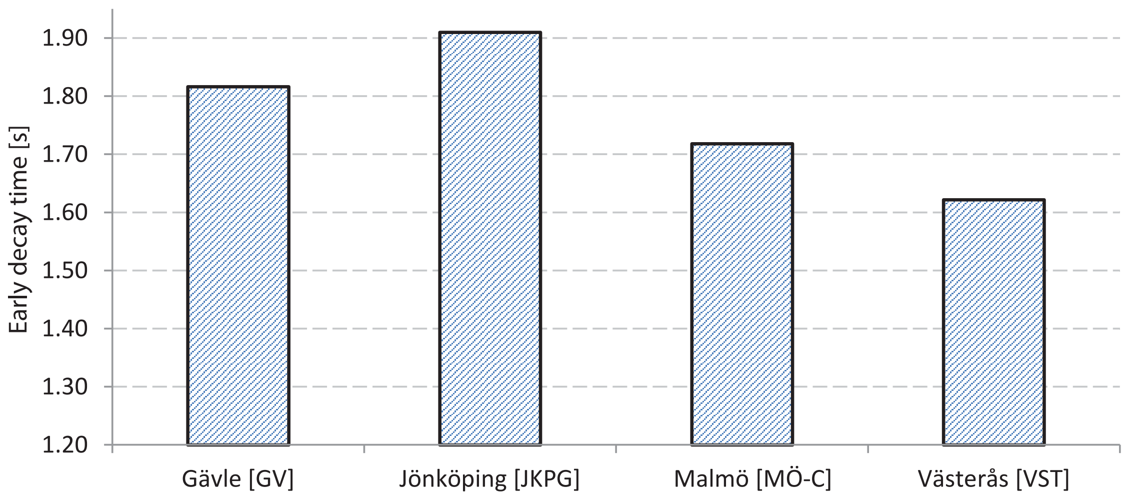

Figure 4.8: Mean measured early decay time for all halls.

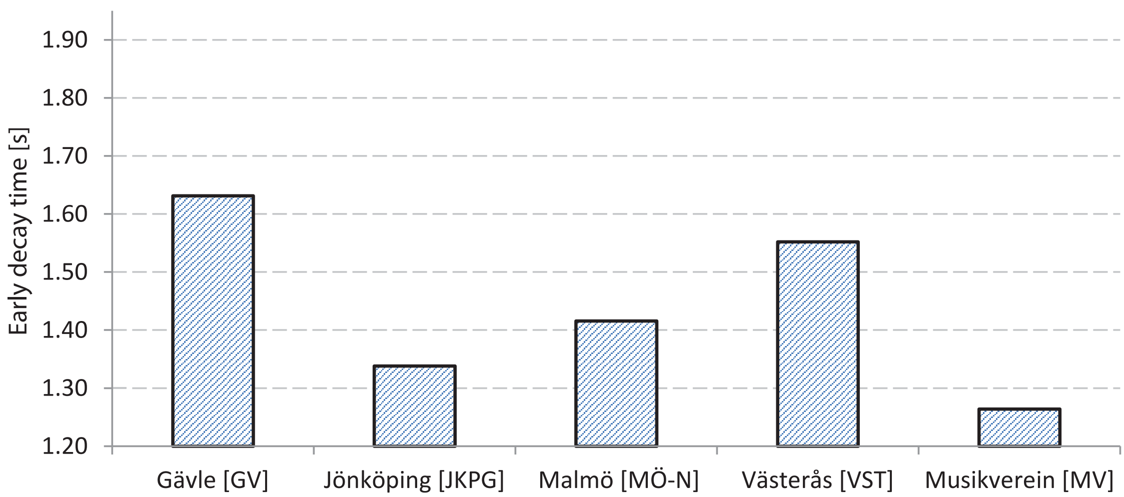

Figure 4.9: Mean calculated early decay time for all halls.

received the lowest grades of all the halls in the surveys, there may be some sort of optimal value for the clarity between these values.

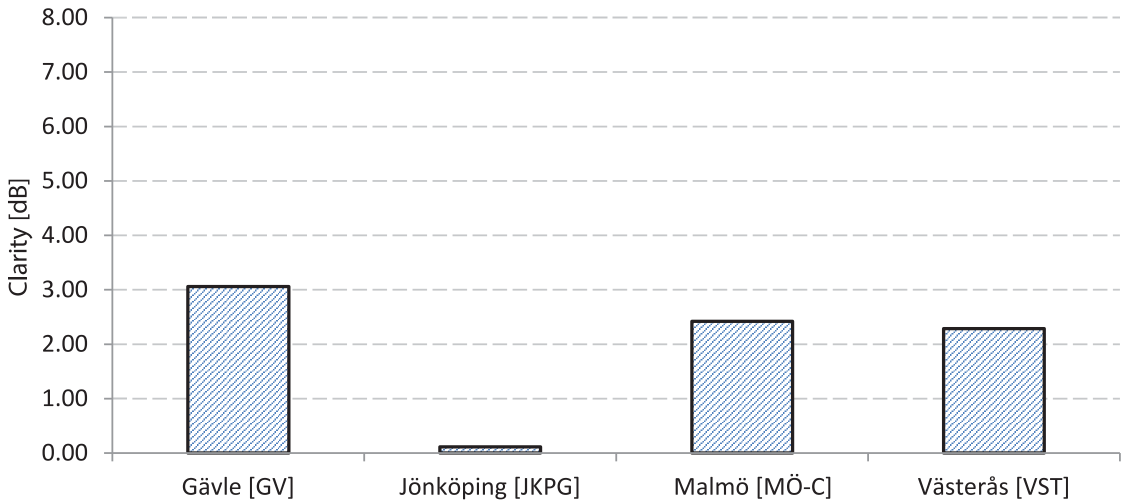

Figure 4.10: Mean measured clarity for all halls.

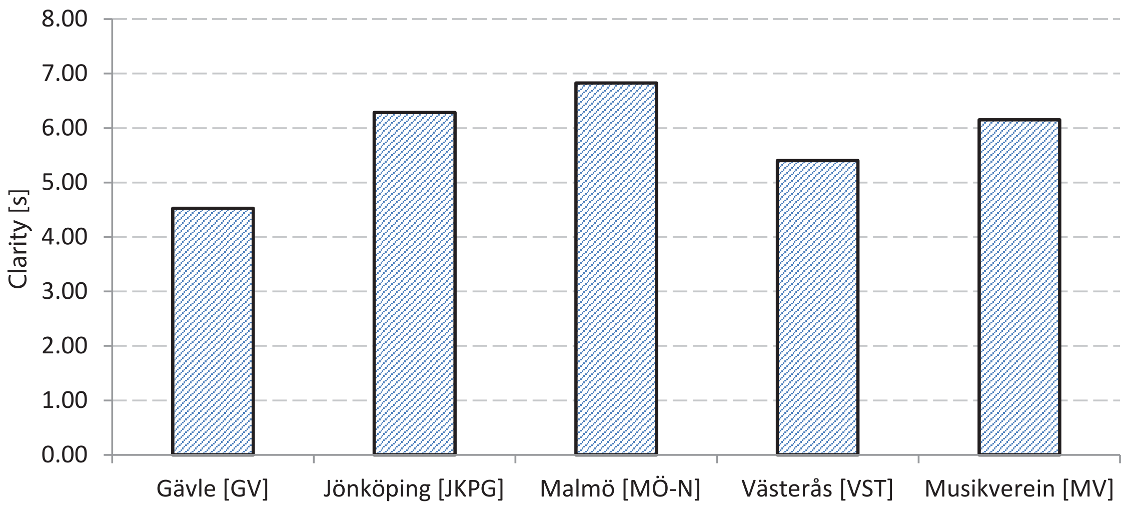

Figure 4.11: Mean calculated clarity for all halls.

Definition for all the halls is displayed in Figures 4.12 and 4.13. Yet again, the calculations seem to overestimate the clarity. As for the measured definition, Jönköping is not as extreme as the clarity measurement, but has quite a similar value to that of Malmö and Västerås. However, Gävle seems to differ the most from the other measured and calculated values.

Early support values are shown in Figures 4.14 and 4.15. The measured values range between a little over -11 dB to a little over -13 dB. The calculated values for the corresponding measured halls are lower. Jönköping has the best correspondence while Gävle has a larger difference of about -11 to -14 dB. The reason for this could be the modelling of the orchestra surface which is rough in CATT-Acoustic without any simulation of furniture surfaces. Note that the calculated MÖ-N value is N/A and is therefore not shown in the graph.

4.2.1 Support

In Table 4.13 and 4.14, the measured support value in location S3 in Jönköping has a asterisk (*) next to the value. The value is very low in comparison to other ST-values at the same position because percussion

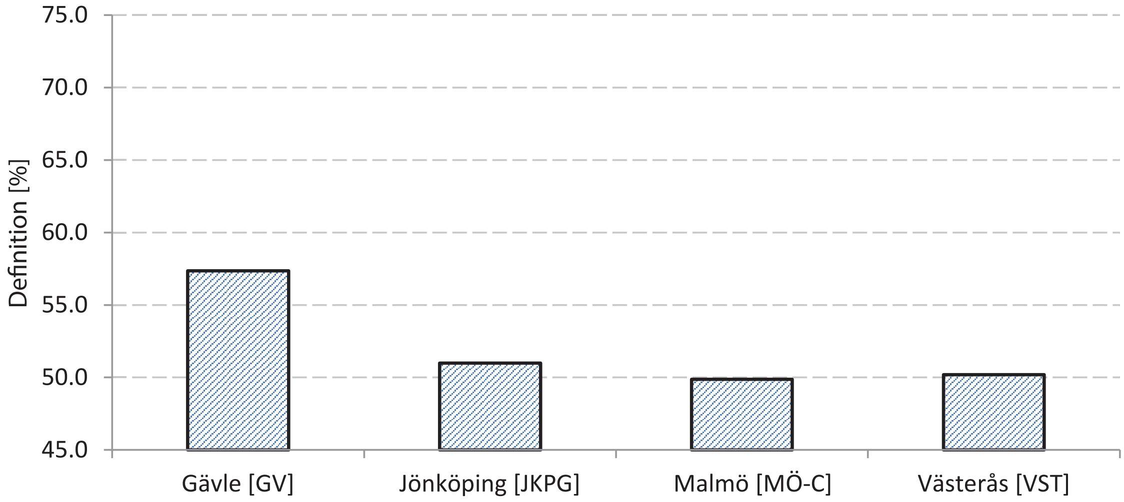

Figure 4.12: Mean measured definition for all halls.

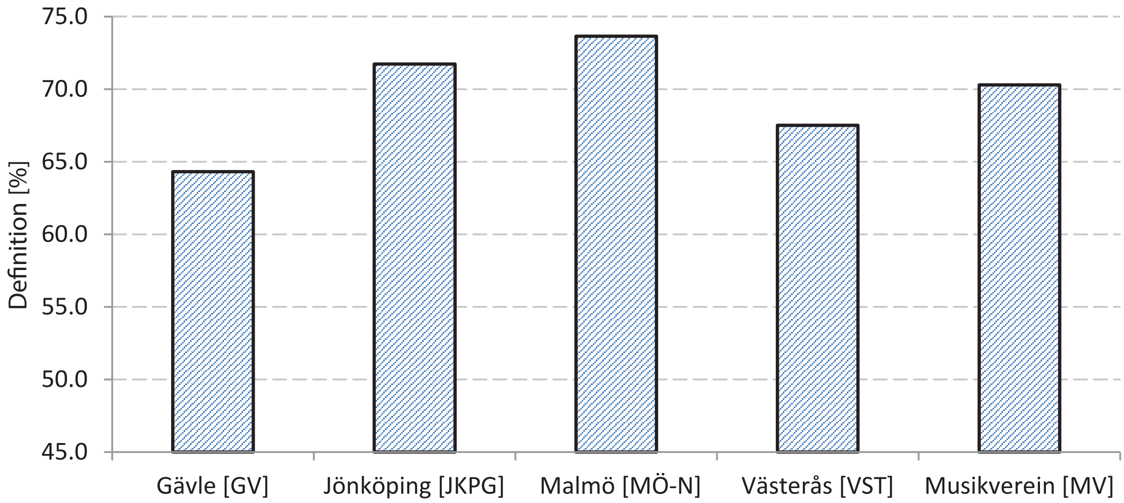

Figure 4.13: Mean calculated definition for all halls.

Figure 4.14: Mean measured early support or ST_{early} for all halls.

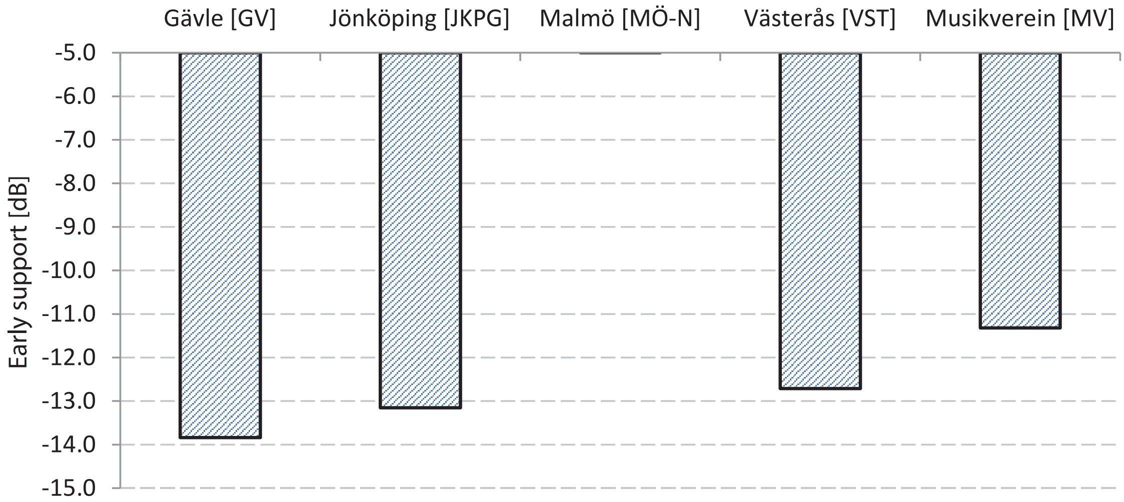

Figure 4.15: Mean calculated early support or ST_{early} for all halls. Note that support for MÖ-N has not been calculated due to lack of time.

Table 4.13: ST_{early} for all positions measured (Meas) and calculated (Calc). Diff is the difference between the measured and calculated result.

	GV			JKPG			VST			MÖ-C	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc
X1	-9.5	-11.1	1.6	-11.2	-14.0	2.8	-10.8	-11.9	1.1	-11.6	-9.6
P1	-12.0	-13.8	1.9	-9.9	-14.3	4.4	-10.0	-12.8	2.9	-12.0	-11.1
P2	-10.2	-14.8	4.6	-16.8	-13.0	3.7	-12.5	-12.9	0.4	N/A	-10.2
P3	-11.9	-13.9	2.0	-13.4	-12.1	1.3	-9.8	-11.9	2.1	-12.5	-11.5
S1	-12.8	-16.4	3.6	-18.8	-12.7	6.1	-11.2	-13.7	2.5	-15.5	-14.1
S2	-10.3	-15.0	4.7	-12.2	-13.8	1.6	-12.5	-13.1	0.7	-14.4	-13.1
S3	-8.8	-11.8	3.0	-3.4*	-12.2	8.8*	-9.3	-12.6	3.4	-11.2	-9.8
Mean	-10.8	-13.8	3.1	-13.7	-13.1	3.3	-10.9	-12.7	1.8	-12.8	-11.3
σ	1.5	1.9	1.3	3.4	0.9	1.8	1.3	0.7	1.1	1.7	1.8

instruments were placed closer than 2 meters from a transducer and there was no possibility to move the large instruments. Therefore, these values have not be accounted for in the mean or the σ.

An observation from Table 4.13 is that standard deviation, or σ, for Jönköping's measured values is larger than that of any other hall with a value of 3.4. The reason for this could be the measurement settings since this was the first hall measured and the RCA output on the microphone pre-amplifier (mic pre) was used. In later tests, the use of RCA yielded an unwanted trigger earlier peak which WinMLS thought was the trigger of direct sound. By switching to XLR, the peak was minimized and measurements were more consistent.

The early support values in Table 4.13 for S3 generally tend to be lower and this may be because percussion instruments placed in the back were usually difficult to move and in close proximity to the transducer. In Västerås, the difference in the measured and calculated values for ST_e have a low mean value as well as a low σ. The most difference is found in position S3 which may be due to proximity of percussion instruments which could not be moved further away. Position P2 is listed as N/A in MÖ-C which is due to the lack of time in performing the support measurement due to size of orchestra and time available for measurements.

As for late support, found in Table 4.14, mean values and σ are far more coherent and the difference between calculations and measurements are decreased. The largest difference is found in JKPG for the measurements which may indicate some sort of error in the support measurement for ST_l. However, the average over the several positions yields a similar result to the mean calculated value. MV has low mean value while Gävle has the highest mean value in both calculation and measurement. In turn, the lower late support may partly contribute the lower grading of Gävle.

Table 4.14: ST_{late} for all positions measured and calculated.

	GV			JKPG			VST			MÖ-C	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc
X1	-13.8	-13.5	0.3	-15.3	-14.9	0.4	-13.0	-15.2	2.2	-15.1	-12.6
P1	-13.6	-13.5	0.1	-16.1	-14.8	1.3	-12.2	-15.7	3.5	-12.0	-16.5
P2	-13.3	-13.7	0.4	-17.1	-14.3	2.8	-13.9	-15.4	1.5	N/A	-16.7
P3	-14.2	-13.4	0.8	-14.7	-14.3	0.4	-12.4	-14.7	2.3	-15.6	-16.5
S1	-12.8	-13.7	0.8	-18.3	-14.1	4.2	-13.6	-15.2	1.6	-14.6	-15.9
S2	-13.3	-13.2	0.1	-12.8	-15.0	2.2	-13.3	-15.4	2.0	-14.4	-16.8
S3	-13.5	-13.5	0.0	-5.7*	-14.3	8.6*	-12.5	-15.0	2.5	-15.6	-13.2
Mean	-13.5	-13.5	0.4	-15.7	-14.5	1.2	-13.0	-15.2	2.2	-14.5	-15.5
σ	0.4	0.2	0.3	1.9	0.3	1.5	0.6	0.3	0.6	1.4	1.9

4.2.2 Lateral fraction

Table 4.15: LF for all halls note that measured values from JKPG and MÖ-C are extremely high.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	31.2	26.4	4.8	47.6	12.9	34.6	15.3	18.0	2.6	56.7	19.5	11.6
P1	50.1*	12.6	37.5*	49.0	8.3	40.7	12.8	10.4	2.5	38.6	7.9	17.4
P2	17.9	17.6	0.3	52.5	12.9	39.6	12.8	17.1	4.4	37.6	11.8	14.9
P3	21.2	15.3	5.9	56.7	14.9	41.8	27.7	14.0	13.7	31.0	10.6	20.1
S1	16.3	18.6	2.3	60.3	12.7	47.5	10.3	19.2	9.0	38.2	18.8	13.3
S2	33.4	17.4	16.0	67.4	18.9	48.5	18.9	12.9	6.0	47.7	14.9	19.5
S3	29.9	21.2	8.7	55.7	11.2	44.5	17.3	18.6	1.4	24.6	17.5	16.3
Mean	25.0	18.4	6.4	55.6	13.1	42.5	16.4	15.7	5.6	39.2	14.4	16.2
σ	7.4	4.4	5.6	6.8	3.3	4.8	5.7	3.4	4.4	10.5	4.4	3.1

As seen in Table 4.15, the high values in the case of JKPG can be explained by the failure of the mic pre. This hypothesis was confirmed during the processing of the results by switching the figure eight and omni-microphone in the LF calculation according to equation (2.10). The result indicated that the LF values were similar which shows that the middle RCA only outputs omni (not omni and figure eight). This was also confirmed by Mats Olsson at Akustikon/Norconsult which pointed out that the top most RCA should have been used. In GV, VST, and MÖ-C the XLR-output was used which yielded the correct microphone characteristics. However, LF in MÖ-C seems quite high as well with a measured mean value of 39.2 percent. ISO 3382-1 states that normally LF should vary between 0.05 and 0.35, or 5 to 35 percent. (ISO 3382-1, 2009, p. 12). However, the range is for positions in the audience and LF-values on stage may vary significantly from the normal values. Most likely the cause of the high values is due to the placement of the microphone and the effect of the surrounding furniture.

4.2.3 Strength

As previously mentioned, the gain switch broke during transportation of equipment when measuring in Gävle and Västerås. Therefore, an amplifier was borrowed from the technicians at the concert halls. In turn, calibration of the loudspeaker and amplifier is impossible to perform and the comparison between halls is not possible. However, parameter of strength or gain is still important in terms of comparisons between different paths within an orchestra. The following Tables 4.16, 4.18, 4.20, and 4.22 present measurements for G-values for the different halls. The key to the right shows the different receiver positions which would represent the mean level of gain experienced by the musicians at that positions from the other six instrument positions. However, keep in mind that the source is considered omni-directional over the frequency range of interest and the instrument may display another directivity pattern than omni-directional, especially at higher frequencies. Using an omni-directional source is a simplification which does not consider instrument directivity, but may also yield a better average since an orchestra consisting of many instruments at different angles may contribute to a vastly different directivity pattern than that of a study with accurate directivity.

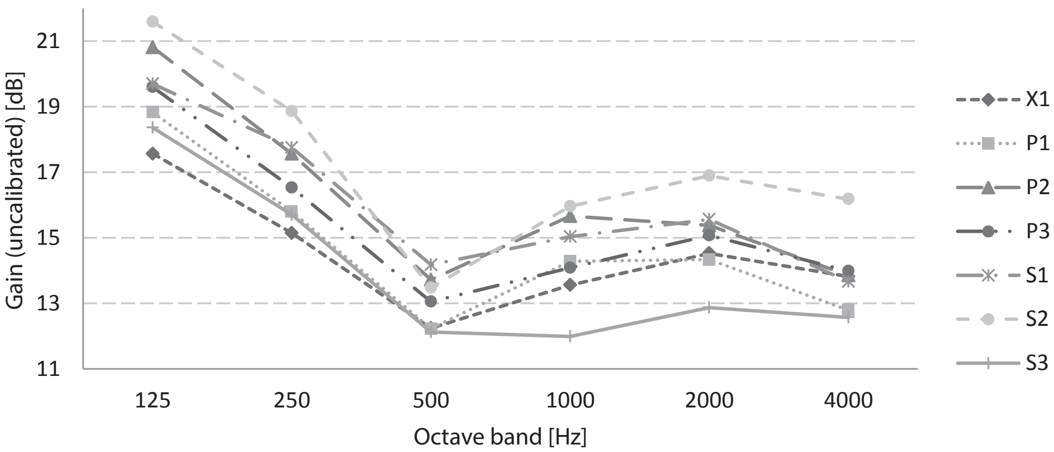

Figure 4.16: Measured gain or strength in Gävle for all src-rec paths.

When comparing Figure 4.16 with Figure 4.17, it is possible to see that the calculated values change slope at around 500 Hz, but the measured values have an even greater dip. Furthermore, the calculated values are almost the same curve offset for each position which the measured curves vary more from different positions. This is not strange due to the lack of detail of furniture in the computer model. The values for the measured hall is much higher, but this may be due to lack of calibration and lack of absorption on stage which is accounted for in an orchestral plane on stage.

In Table 4.16, S2 has higher G for most octave bands except for at 500 Hz. At 500 Hz there is a dip for all the halls. No clear explanation for this could be found, but it may have something to do with a comb filter effect and interfering reflections from side walls as well as overhead reflectors. Strength decays with distance and in position S2 the gain is higher which may be caused by the close proximity of other instrument positions.

S3 has lower values than any other position in the higher octave bands. S3 is the positions located in the back towards the left side of the stage, as seen from the conductor, and usually represents the position of the horn section elevated on a set of risers. An explanation for the attenuation of the higher frequencies may be

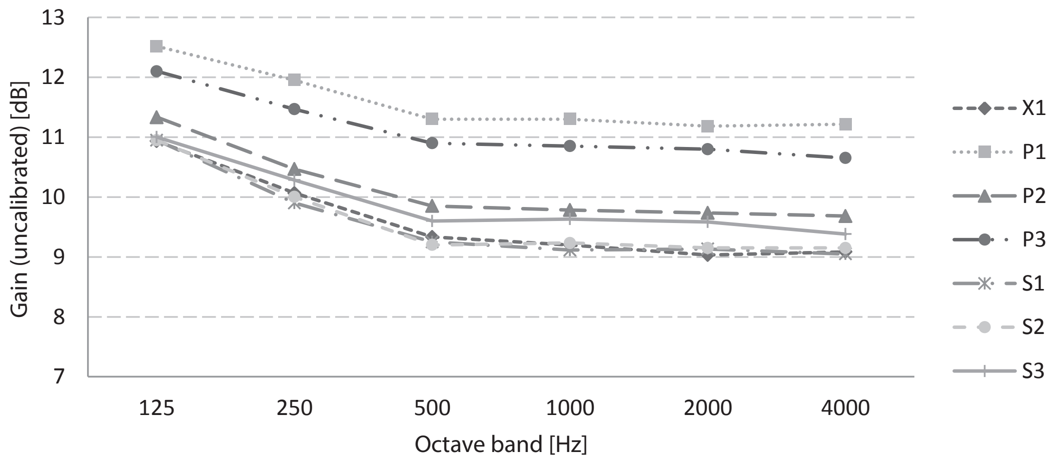

Figure 4.17: Calculated gain or strength in Gävle for all src-rec paths.

caused by the height differences and presence of furniture which diffuses higher frequency sounds.

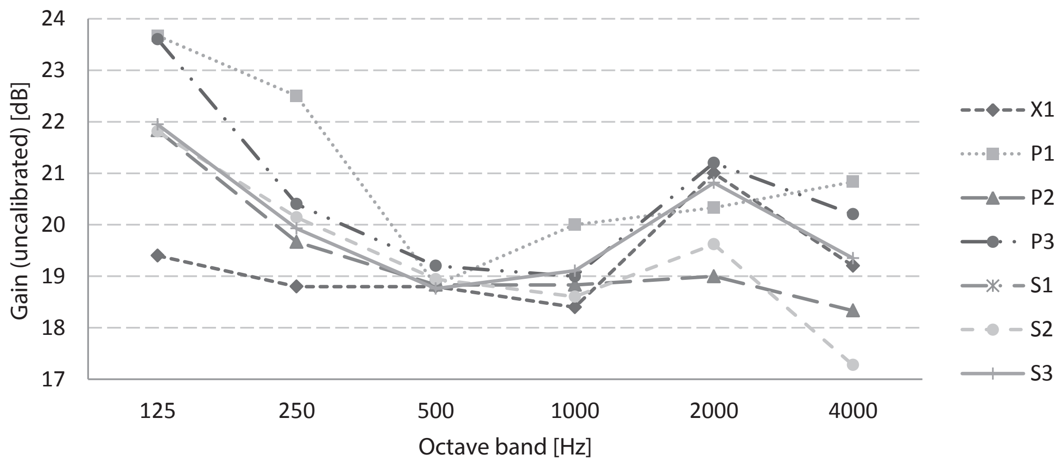

Figure 4.18: Measured gain or strength in Jönköping for all src-rec paths.

In Jönköping, as seen in Figure 4.18, measured positions seem to vary vastly in comparison to other measured halls. However the same dip at 500 Hz is present which could mean that it could be some sort of physical effect caused by the empty furniture on stage. The calculations in Figure 4.19, as with Jönköping, seem to lack the 500 Hz dip and all have a similar slope. However, S2 seems to have the lowest gain which could be explained by that the extra position X1 was measured in a location closer to S1 and therefore S2 in Jönköping lacks the extra contribution from the brass section at the back.

The measured gain in Västerås is similar to that of Gävle as seen in Figure 4.20. However, the spread between different positions for calculations as seen in Figure 4.21 in Västerås is less prominent and there are no positions which vary vastly from the others.

Note that the measured and calculated values for Malmö are not the same hall. Measurements have been made in the old hall and the calculations are done in the CATT-Acoustic model for the new hall which has not yet finished construction. In the measurement for Malmö, in Figure 4.22, there is yet another large dip at 500 Hz and an small peak at 2000 Hz.

As for the calculation in Malmö's new concert hall, shown in Figure 4.23, it has similar tendencies to that of Västerås with a slightly larger difference in gain of 1 dB. The position with the lowest gain is that of S1, which is also true in Västerås.

Gain at 125 Hz or G_{125} was according to both Dammerud and Beranek an alternative measure to BR

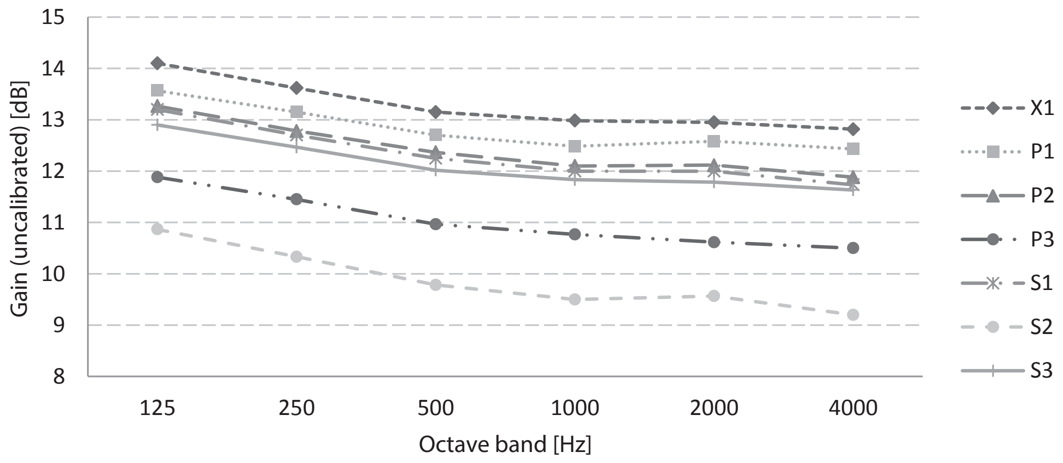

Figure 4.19: Measured gain or strength in Jönköping for all src-rec paths.

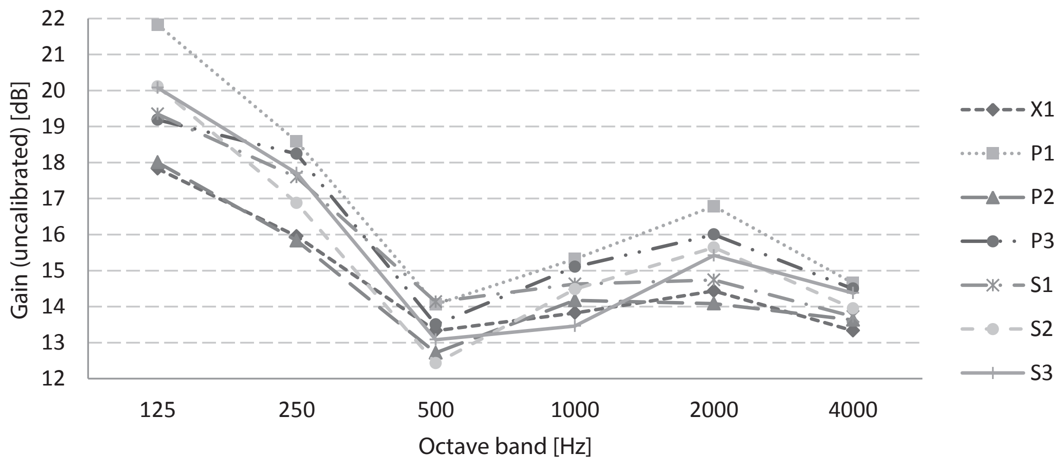

Figure 4.20: Measured gain or strength in Västerås for all src-rec paths.

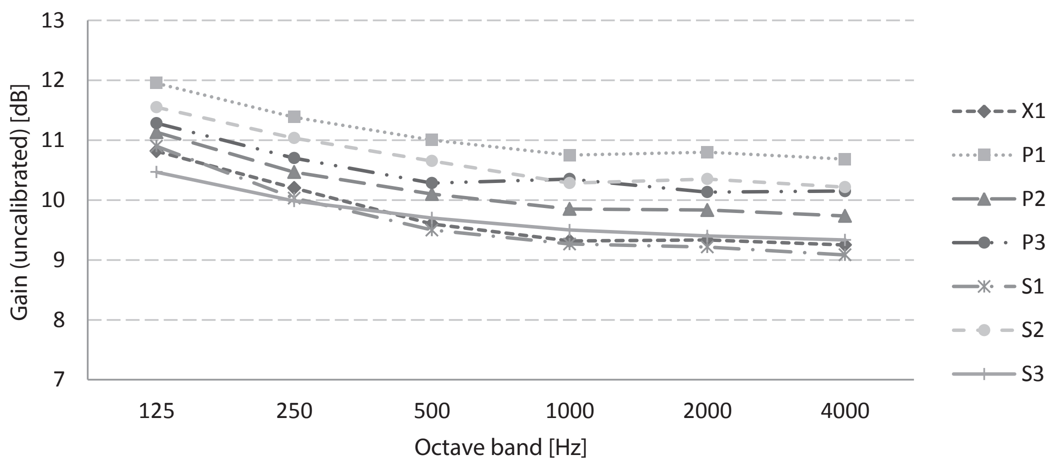

Figure 4.21: Calculated gain or strength in Västerås for all src-rec paths.

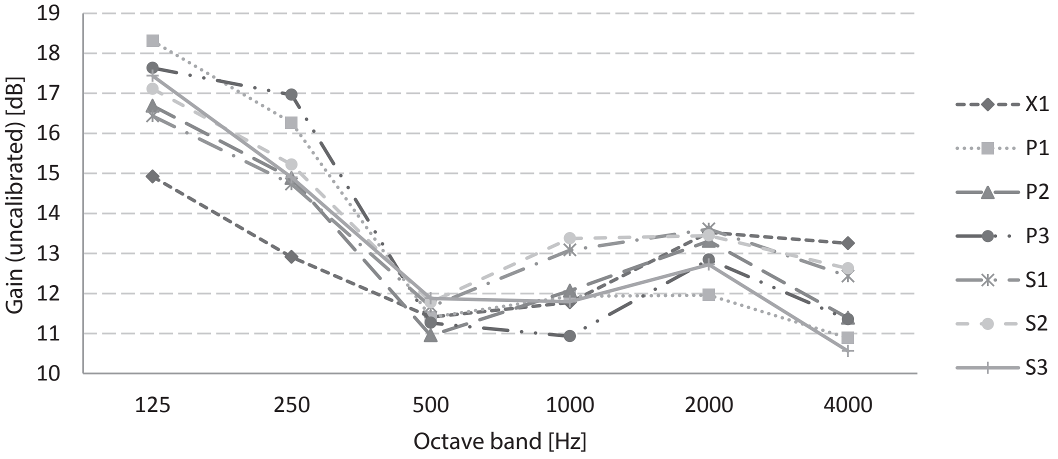

Figure 4.22: Measured gain or strength in Malmö for all src-rec paths.

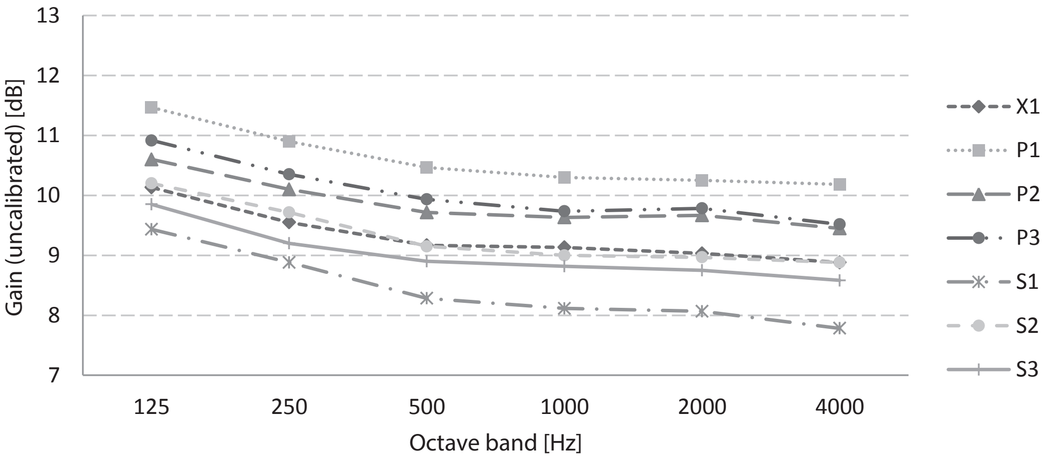

Figure 4.23: Calculated gain or strength in Malmö for all src-rec paths.

for determining the warmth of acoustic conditions in rooms. G_{125} for all measurements and calculations are displayed in Table 4.16. In one of the positions in Jönökping, the measurement is not applicable due to the lack of excitation at 125 Hz. This also highlights the issue that the B& K omni-directional loudspeaker used for the measurements yields a better EDR in higher frequencies and at 125 Hz there may be reason to suspect that the loudspeaker is not sufficient.

Table 4.16: Strength at 125 Hz or G_{125} for all measurements and calculations.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	17.6	10.9	6.6	19.4	14.1	5.3	17.8	10.8	7.0	14.9	10.1	13.0
P1	18.8	12.5	6.3	23.7	13.6	10.1	21.8	12.0	9.9	18.3	11.5	12.4
P2	20.8	11.3	9.5	21.8	13.3	8.6	18.0	11.1	6.9	16.7	10.6	12.4
P3	19.6	12.1	7.5	23.6	11.9	11.7	19.2	11.3	7.9	17.6	10.9	10.7
S1	19.7	11.0	8.7	N/A	13.2	N/A	19.3	10.9	8.4	16.4	9.4	11.8
S2	21.6	11.0	10.6	21.8	10.9	10.9	20.1	11.6	8.6	17.1	10.2	10.2
S3	18.4	11.0	7.4	21.9	12.9	9.0	20.1	10.5	9.6	17.4	9.9	12.1
Mean	19.5	11.4	8.1	22.0	12.8	9.3	19.5	11.2	8.3	16.9	10.4	11.8
σ	1.4	0.7	1.6	8.5	1.1	4.1	1.4	0.5	1.2	1.1	0.7	1.0

However, an interesting observation from Table 4.16 is that G_{125} in Jönköping has an extremely high σ for the measurements compared to any other hall. This further proves that something may be strange with the measurements in this hall, especially because all other halls seem to have similar standard deviations.

4.2.4 Definition

Table 4.17: Definition of $D50$ for all halls.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	57.4	61.9	4.5	51.0	73.6	22.6	50.2	62.9	12.7	49.9	72.1	72.2
P1	64.6	70.2	5.6	75.3	76.7	1.3	64.3	73.1	8.8	65.6	78.4	75.9
P2	60.9	63.8	2.9	62.5	73.7	11.2	56.3	64.9	8.6	55.9	74.2	73.2
P3	61.3	70.4	9.1	65.9	68.7	2.8	59.7	70.4	10.7	56.5	76.2	66.2
S1	55.4	62.3	6.8	43.4	73.4	29.9	51.0	67.2	16.2	47.1	70.3	71.0
S2	58.8	58.7	0.1	53.7	62.6	8.8	56.5	69.8	13.3	51.3	73.1	60.6
S3	59.6	62.9	3.4	67.6	73.6	6.0	57.7	64.4	6.6	60.3	71.3	73.1
Mean	59.7	64.3	4.6	59.9	71.7	11.8	56.5	67.5	11.0	55.2	73.6	70.3
σ	3.0	4.4	2.9	11.0	4.7	10.6	4.9	3.7	3.3	6.4	2.8	5.2

In Table 4.17 the definition for all measurements and calculations are displayed. The highest mean values are found in MÖ-N, closely followed by Jönköping, and Musikverein. The lowest values are found in MÖ-C and Västerås. The highest σ us found in the measurements in Jönköping which further points towards faulty measurements. However, the measured values in Malmö's old venue is also quite high and could be a reason for the great difference experienced in different parts of the orchestra. Moreover, Figures 4.24 and 4.25 show D_{50} for different positions the measurements and calculations respectively.

4.2.5 Clarity

As mentioned in the theory section, C_{80} is expected to have a value between -5 to +5 dB. Furthermore, Beranek suggests a $C_{80}(3)$ for unoccupied rooms which should have a resulting value between +1 and +5 dB and between -1 to -4 dB in an occupied state.

As seen in Table 4.18, measured values mostly fall within Beranek's suggested range although it is only averaged over 500 Hz and 1 kHz octave band. Note that in every calculation using CATT-Acoustic, the

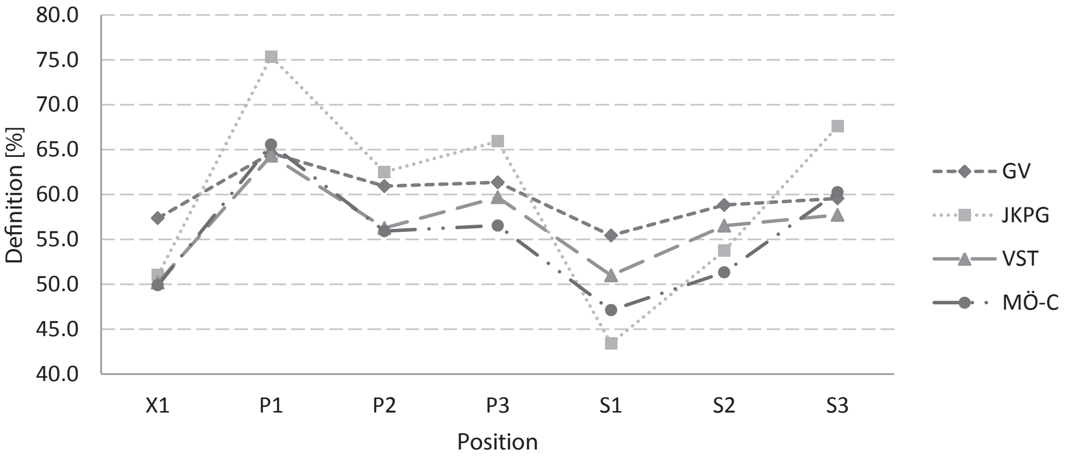

Figure 4.24: Measured definition for all halls and the numerical data is found in Table 4.17.

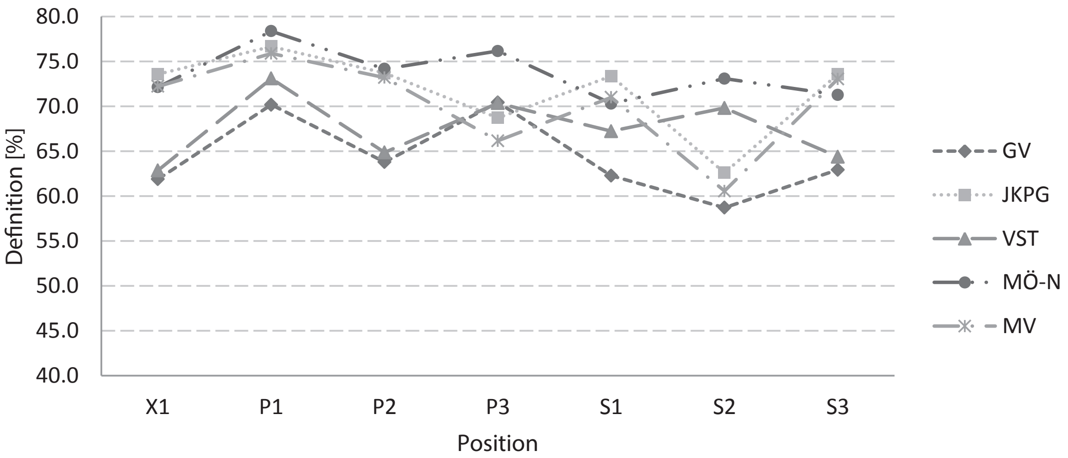

Figure 4.25: Calculated definition for all halls and the numerical data is found in Table 4.17.

Table 4.18: Clarity of C_{80} for all the studied halls with an average over 500 and 1000 octave band.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	3.1	4.0	0.9	0.1	7.7	7.5	2.3	4.7	2.4	2.4	6.8	6.9
P1	4.7	5.8	1.1	5.3	7.2	1.9	4.9	6.1	1.2	5.2	8.0	6.9
P2	3.7	4.4	0.7	2.4	6.8	4.4	3.2	5.1	1.8	3.3	7.1	7.1
P3	4.2	5.9	1.7	3.6	5.4	1.8	3.9	5.9	2.0	3.5	7.3	5.1
S1	2.8	4.0	1.2	0.7	6.6	5.9	2.7	5.3	2.6	1.9	5.9	6.3
S2	3.0	3.6	0.6	2.6	4.1	1.4	3.4	5.8	2.4	2.6	6.5	4.1
S3	3.5	4.0	0.5	5.5	6.3	0.8	3.5	5.0	1.5	4.4	6.2	6.6
Mean	3.6	4.5	1.0	2.9	6.3	3.4	3.4	5.4	2.0	3.3	6.8	6.1
σ	0.7	0.9	0.4	2.1	1.2	2.6	0.9	0.5	0.5	1.2	0.7	1.1

calculated C_{80} exceeds that of the measured value. MV and JKPG have high values with mean values of 6.1 and 6.3 respectively. The measured values for JKPG is considered to be out of range for positions X1, P1, S1, and S3. Yet, the average of all values is still within the range. The reason for this variation among positions could be caused by faults in the measurement. One could also challenge the usability of C_{80} measurements when the values change considerably if the hall is occupied or not.

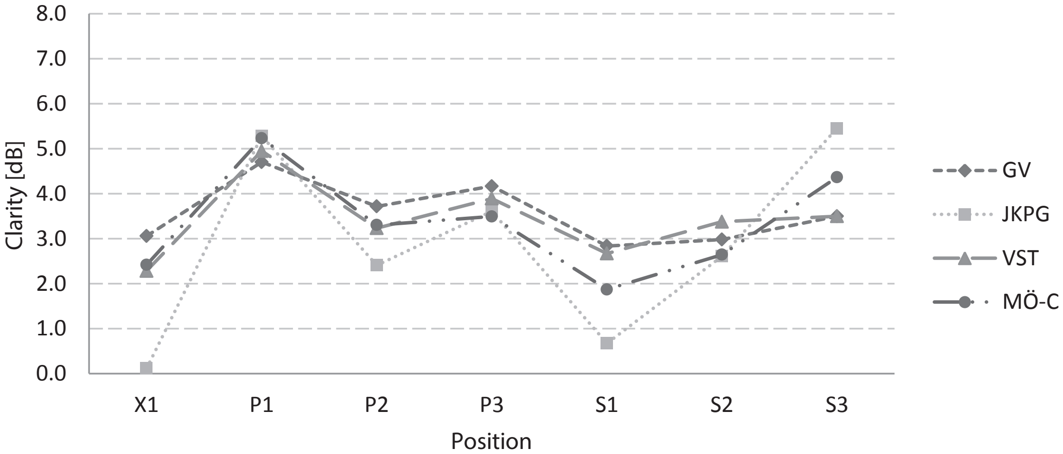

Figure 4.26: Measured clarity for all halls and the numerical data is found in Table 4.18.

General tendencies of Clarity values for different positions in apparent in Figure 4.26. However, these same tendencies are not present in the calculated values in Figure 4.27.

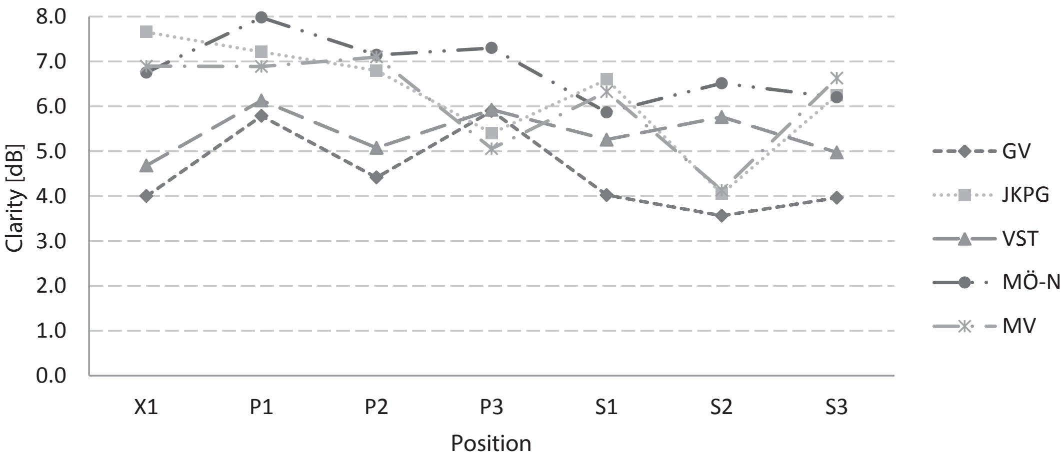

Figure 4.27: Calculated clarity for all halls and the numerical data is found in Table 4.18.

In order to verify the difference between C_{80} and $C_{80}(3)$ Table 4.19 displays the $C_{80}(3)$ for all measurements and calculations. There is not much significant change, only slight variation between the numbers. The difference could be greater when measured in the audience, but for this study C_{80} is investigated further and not $C_{80}(3)$.

4.2.6 Early Decay Time

The EDT displayed in Table 4.20 are slightly shorter than that of the top ranked halls according to Beranek's studies. JKPG measurements have a higher σ with a value of 0.27 in comparison to the 0.13 in calculations. The mean difference between calculation and measurements is large at 0.31 and this may further support that JKPG measurements may be faulty to some extent. Position P2 has a 0.53 second difference between

Table 4.19: *Clarity of $C_{80}(3)$ for all the studied halls with an average over 500, 1000, and 2000 octave band.*

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	3.0	4.1	1.1	0.0	7.6	7.7	2.4	4.7	2.2	2.2	6.9	7.0
P1	4.9	5.8	0.9	4.9	7.2	2.3	4.7	6.2	1.5	5.2	8.0	7.0
P2	3.8	4.5	0.7	2.1	6.8	4.7	3.2	5.2	1.9	3.5	7.3	7.2
P3	4.3	5.8	1.6	3.4	5.4	2.0	3.8	5.9	2.1	3.5	7.3	5.2
S1	2.7	4.1	1.3	0.4	6.7	6.2	2.7	5.3	2.6	1.8	5.9	6.3
S2	3.0	3.6	0.7	2.7	4.2	1.5	3.3	5.8	2.4	2.8	6.5	4.1
S3	3.4	4.0	0.6	5.5	6.3	0.8	3.2	5.0	1.8	4.1	6.2	6.7
Mean	3.6	4.6	1.0	2.7	6.3	3.6	3.3	5.4	2.1	3.3	6.9	6.2
σ	0.8	0.9	0.4	2.1	1.2	2.6	0.7	0.5	0.4	1.2	0.7	1.2

Table 4.20: *Early decay time or EDT for all halls in study.*

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	1.82	1.67	0.15	1.91	1.22	0.70	1.62	1.50	0.13	1.72	1.31	1.56
P1	1.62	1.47	0.15	1.30	1.23	0.07	1.36	1.58	0.21	1.39	1.35	1.47
P2	1.71	1.68	0.04	1.74	1.22	0.53	1.55	1.57	0.02	1.69	1.28	1.56
P3	1.68	1.51	0.17	1.35	1.39	0.03	1.46	1.49	0.03	1.60	1.41	1.47
S1	1.70	1.67	0.03	1.90	1.55	0.36	1.61	1.59	0.02	1.88	1.60	1.60
S2	1.77	1.70	0.07	1.85	1.46	0.39	1.58	1.48	0.10	1.76	1.46	1.53
S3	1.84	1.73	0.11	1.45	1.32	0.13	1.51	1.67	0.17	1.43	1.52	1.59
Mean	1.73	1.63	0.10	1.64	1.34	0.31	1.53	1.55	0.10	1.64	1.42	1.54
σ	0.08	0.10	0.05	0.27	0.13	0.25	0.09	0.07	0.08	0.18	0.12	0.05

calculation and measurement and this is the largest difference found in the EDT table.

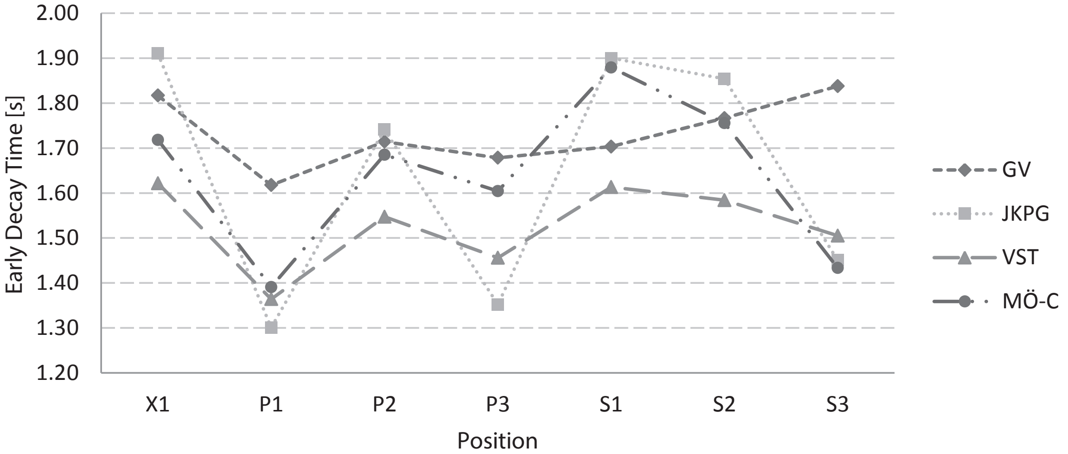

Figure 4.28: Measured early decay time for all halls and the numerical data is found in Table 4.20.

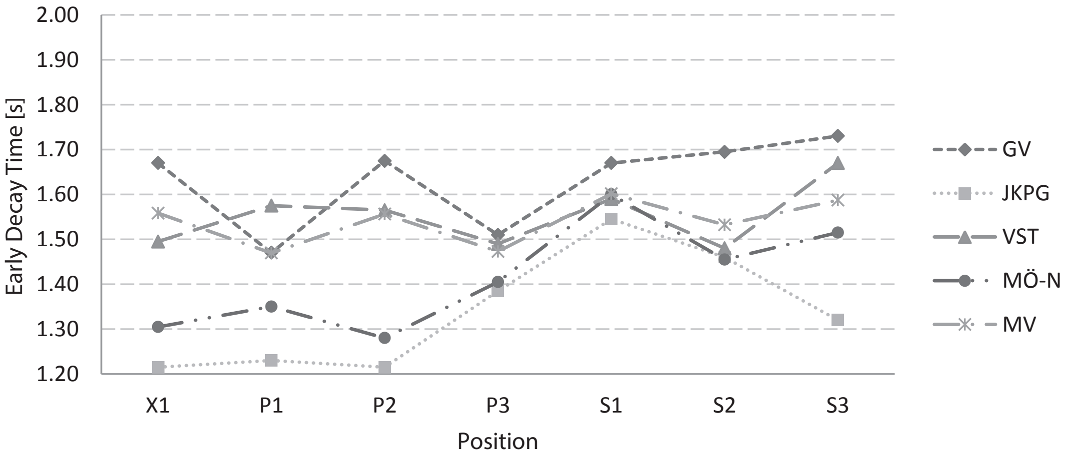

Figure 4.29: Calculated early decay time for all halls and the numerical data is found in Table 4.20.

Figures 4.28 and 4.29 show the variation of EDT over the seven positions in this study. It is observed that the measured EDT generally is longer than that of the calculated EDT. However, the lack of an audience, or absorption, during the measurement may explain the longer EDT.

4.2.7 Reverberation Time

The reverberation time measurements and calculations are shown in Table 4.21 and generally a very low variation is observed. Västerås has a short reverberation time in the calculations which is consistent with the measurements and very little variation is seen in VST. MÖ-N and MV have long RT at about 2 s with MÖ-C slightly shorter than the new hall MÖ-N.

However, an observation from Jönköping is that usually textiles on the walls are used during rehearsals by sound technicians. These were elevated and removed during the measurements which might actually make the RT longer than musicians are usually exposed to. Therefore, this setting in the CATT-Acoustic model has been preserved. Furthermore, the CATT-Acoustic model is the same used by Emelie Olofsson who started the work on this thesis.

In addition to RT, BR and TR have been calculated according to equations (2.11) and (2.12). These ratios are found in Tables 4.22 for BR and 4.23 for TR. As with RT, the σ is low and only small differences can be

Table 4.21: RT time or T_{30} for all halls in study.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	1.90	1.98	0.08	2.02	1.82	0.20	1.72	1.76	0.04	2.00	2.10	2.00
P1	1.88	1.97	0.09	1.97	1.85	0.12	1.72	1.74	0.02	1.99	2.09	2.02
P2	1.86	1.96	0.09	2.01	1.86	0.15	1.75	1.75	0.00	1.98	2.09	2.04
P3	1.87	1.94	0.07	1.98	1.85	0.13	1.73	1.73	0.00	2.00	2.09	2.04
S1	1.88	1.98	0.09	2.00	1.87	0.14	1.75	1.79	0.03	2.01	2.11	2.04
S2	1.88	1.98	0.09	1.98	1.89	0.09	1.73	1.75	0.01	1.99	2.10	2.06
S3	1.88	1.96	0.08	1.96	1.86	0.10	1.74	1.76	0.02	2.00	2.08	2.01
Mean	1.88	1.96	0.09	1.99	1.86	0.13	1.73	1.75	0.02	2.00	2.09	2.03
σ	0.01	0.01	0.01	0.02	0.02	0.04	0.01	0.02	0.01	0.01	0.01	0.02

Table 4.22: BR for all halls.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	1.14	1.32	0.17	1.02	1.10	0.07	1.08	1.15	0.08	1.19	1.09	1.08
P1	1.16	1.31	0.15	1.03	1.09	0.07	1.10	1.17	0.07	1.17	1.09	1.10
P2	1.16	1.34	0.18	1.05	1.08	0.03	1.07	1.16	0.08	1.20	1.09	1.08
P3	1.17	1.34	0.17	1.05	1.11	0.06	1.10	1.17	0.06	1.19	1.09	1.11
S1	1.16	1.31	0.15	1.02	1.09	0.07	1.08	1.15	0.07	1.17	1.09	1.10
S2	1.18	1.32	0.14	1.08	1.09	0.01	1.08	1.16	0.08	1.22	1.10	1.09
S3	1.17	1.33	0.17	1.12	1.08	0.04	1.09	1.16	0.06	1.14	1.10	1.11
Mean	1.16	1.32	0.16	1.05	1.09	0.05	1.09	1.16	0.07	1.18	1.09	1.10
σ	0.01	0.01	0.01	0.04	0.01	0.02	0.01	0.01	0.01	0.03	0.01	0.01

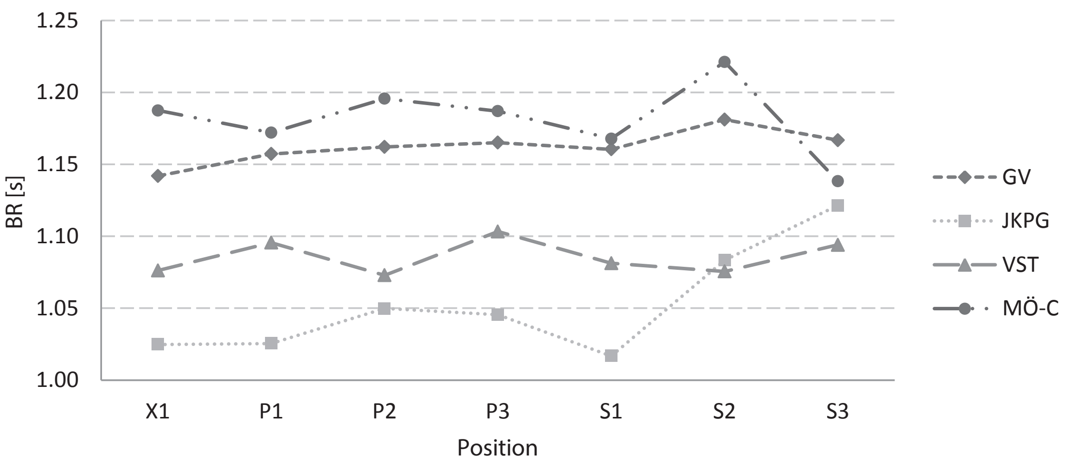

Figure 4.30: Measured bass ratio for all halls and the numerical data is found in Table 4.22.

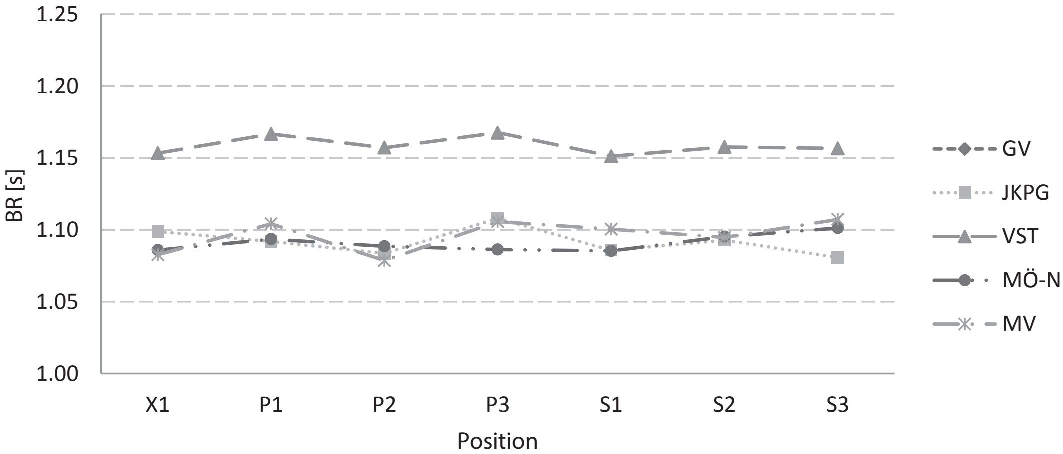

Figure 4.31: Calculated bass ratio for all halls and the numerical data is found in Table 4.22.

Table 4.23: TR for all halls.

	GV			JKPG			VST			MÖ-C	MÖ-N	MV
Position	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Diff	Meas	Calc	Calc
X1	0.76	0.89	0.13	0.78	0.86	0.09	0.83	0.90	0.07	0.78	0.87	0.79
P1	0.75	0.89	0.14	0.81	0.87	0.06	0.81	0.92	0.11	0.77	0.87	0.78
P2	0.76	0.89	0.13	0.78	0.86	0.08	0.82	0.92	0.10	0.79	0.87	0.77
P3	0.76	0.91	0.16	0.79	0.87	0.08	0.80	0.94	0.14	0.77	0.87	0.78
S1	0.76	0.87	0.11	0.80	0.88	0.09	0.84	0.91	0.07	0.78	0.87	0.77
S2	0.77	0.89	0.12	0.79	0.86	0.06	0.81	0.91	0.10	0.78	0.87	0.78
S3	0.76	0.93	0.17	0.80	0.85	0.05	0.80	0.92	0.12	0.76	0.87	0.79
Mean	0.76	0.90	0.14	0.79	0.86	0.07	0.82	0.92	0.10	0.78	0.87	0.78
σ	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.01

seen among the different positions.

4.3 Correlation

This section interprets the correlation between subjective judgment and objective measurements.

Table 4.24: Correlation coefficients between subjective and objective parameters in Gävle.

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
OAI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SUP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DYN	<u>-0.58</u>	-0.28	0.23	0.36	0.30	-0.33	-0.22	0.32	<u>0.46</u>	0.31	-0.20
ENS	-0.32	-0.06	0.00	0.24	<u>0.49</u>	-0.02	-0.08	0.35	**0.63**	**0.62**	0.12
SPL	0.07	0.24	-0.12	-0.08	-0.19	0.04	0.17	0.14	-0.07	0.21	0.00
COL	0.09	-0.12	-0.18	0.04	<u>0.43</u>	0.39	-0.20	0.33	<u>0.45</u>	0.36	0.28
HS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
REV	-0.26	0.05	0.03	0.01	0.02	-0.31	0.11	0.11	0.07	0.01	-0.08

Table 4.24 shows the correlation in Gävle. As for OAI in Gävle, outliers have been determined according to Figure 4.5 and the value of the Min, Q_1, Median, Q_3, and Max all coincide at a value of 7. This implies that the σ for the subjective judgment is equal to zero and, in turn, division by zero according to equation (2.23) yields the status of N/A.

In Gävle, SUP also has a small range since Q_1, Median, and Q_3 all coincide at a value of 7. On the other hand, Min and Max vary from 6 to 8 and therefore Spearman's correlation can be evaluated. Only one correlation value exceeds 0.60 in Table 4.24, this is ENS - BR which has a value of 0.61 which according to Table 2.5 signifies that there is a strong monotonic relationship between ENS and BR.

Table 4.25: Correlation coefficients between subjective and objective parameters in Jönköping.

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
OAI	-0.25	0.02	0.13	-0.09	0.00	0.36	-0.04	0.10	0.00	0.13	0.20
SUP	-0.19	0.21	0.00	-0.16	-0.08	0.11	0.20	0.21	-0.08	0.02	0.23
DYN	-0.20	0.05	0.08	-0.07	0.00	0.21	0.05	0.10	0.00	0.06	0.18
ENS	-0.24	0.05	0.10	-0.22	-0.02	**0.66**	-0.28	0.00	-0.02	0.00	0.14
SPL	-0.19	0.27	-0.06	-0.38	-0.24	**0.60**	-0.19	0.00	-0.24	-0.09	0.12
COL	<u>-0.44</u>	-0.03	0.24	-0.14	0.28	<u>0.45</u>	-0.04	0.11	0.28	0.09	<u>0.54</u>
HS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
REV	0.36	0.32	-0.35	-0.31	<u>-0.49</u>	0.14	-0.36	-0.28	<u>-0.49</u>	-0.08	<u>-0.44</u>

Table 4.26: Correlation coefficients between subjective and objective parameters in Västerås.

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
OAI	-0.04	-0.24	0.30	0.30	0.20	0.00	-0.23	0.00	0.38	-0.03	-0.14
SUP	-0.16	-0.24	0.32	0.32	0.16	0.03	-0.28	0.04	<u>0.44</u>	-0.08	-0.16
DYN	0.04	0.09	-0.01	-0.01	0.02	-0.11	<u>-0.50</u>	-0.26	0.27	-0.29	0.15
ENS	0.09	0.11	-0.14	-0.14	-0.10	-0.28	-0.33	-0.29	0.07	-0.32	0.25
SPL	0.09	-0.23	0.26	0.26	-0.15	0.04	-0.09	-0.02	0.29	-0.05	-0.21
COL	-0.07	-0.01	-0.03	-0.03	-0.35	-0.10	<u>-0.56</u>	-0.35	0.08	<u>-0.59</u>	0.10
HS	<u>-0.42</u>	0.10	-0.02	-0.02	-0.23	0.33	-0.10	0.20	-0.10	-0.17	-0.14
REV	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

As seen in Table 4.27 the correlation between subjective and objective parameters is relatively low; however, there are some cases with moderate correlation like COL which moderately correlates to EDT, C_{80}, and D_{50}.

Table 4.27: *Correlation coefficients between subjective and objective parameters in Malmö.*

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
OAI	-0.34	-0.02	0.13	0.13	0.23	-0.07	-0.37	0.55	0.17	0.04	0.17
SUP	-0.15	-0.26	0.26	0.26	-0.09	-0.26	-0.01	0.32	0.15	-0.23	-0.01
DYN	-0.29	0.11	-0.14	-0.14	0.07	0.10	0.12	0.26	-0.24	0.09	0.25
ENS	-0.25	-0.01	0.08	0.08	0.10	-0.13	-0.26	0.33	0.07	-0.01	0.16
SPL	-0.17	-0.12	0.18	0.18	0.00	-0.22	-0.10	0.16	0.15	0.00	0.06
COL	-0.09	-0.52	0.51	0.51	-0.07	-0.27	0.21	0.37	0.39	-0.35	-0.29
HS	-0.10	-0.34	0.40	0.40	0.04	-0.09	0.01	0.36	0.42	-0.13	-0.21
REV	-0.08	-0.13	0.04	0.04	-0.19	0.00	0.28	0.14	-0.13	-0.13	0.03

This could be explained by the lack of deviation in the COL parameter from the survey which in turn yields a lower σ and therefore a higher rank.

Moreover, HS seems to be correlated to C_{80}, D_{50}, and G_{125}. The highest correlation for the Malmö concert hall is OAI and the late support ST_l. However, this correlation does not exist in any of the other halls and can therefore not be considered as a significant correlation.

Table 4.28: *Correlation coefficients between subjective and objective parameters in all the measured halls.*

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
OAI	-0.21	-0.08	0.19	0.11	0.14	0.10	-0.22	0.22	0.19	0.05	0.08
SUP	-0.17	-0.10	0.19	0.14	0.00	-0.04	-0.03	0.19	0.17	-0.10	0.02
DYN	-0.25	-0.01	0.04	0.04	0.10	-0.03	-0.14	0.10	0.12	0.04	0.10
ENS	-0.18	0.02	0.01	-0.01	0.12	0.06	-0.24	0.10	0.19	0.07	0.17
SPL	-0.05	0.04	0.07	0.00	-0.14	0.12	-0.05	0.07	0.03	0.02	-0.01
COL	-0.13	-0.17	0.14	0.09	0.07	0.12	-0.15	0.11	0.30	-0.12	0.16
HS	-0.26	-0.12	0.19	0.19	-0.09	0.12	-0.04	0.28	0.16	-0.15	-0.17
REV	0.01	0.08	-0.09	-0.09	-0.22	-0.06	0.01	-0.01	-0.18	-0.07	-0.16

As seen in Table 4.28, there are only weak monotonic relationships found between subjective and objective parameters. Therefore, it is unlikely that a monotonic relation between the parameters exists.

Table 4.29: *Correlation coefficients between objective parameters with themselves for all halls included in survey.*

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{125}	BR	TR
T_{30}	**1.00**	0.30	-0.50	-0.43	-0.26	-0.08	-0.09	-0.48	-0.29	-0.46	-0.11
EDT	0.30	**1.00**	**-0.78**	**-0.81**	-0.30	0.17	-0.15	-0.30	**-0.64**	-0.10	0.33
C_{80}	-0.50	**-0.78**	**1.00**	**0.95**	0.13	0.06	0.32	0.31	0.54	0.25	-0.46
D_{50}	-0.43	**-0.81**	**0.95**	**1.00**	0.25	-0.06	0.31	0.32	**0.66**	0.29	-0.50
G	-0.26	-0.30	0.13	0.25	**1.00**	0.08	-0.11	0.44	**0.61**	0.33	0.27
LF	-0.08	0.17	0.06	-0.06	0.08	**1.00**	0.12	0.15	-0.08	0.21	-0.12
ST_e	-0.09	-0.15	0.32	0.31	-0.11	0.12	**1.00**	0.33	-0.10	0.37	-0.22
ST_l	-0.48	-0.30	0.31	0.32	0.44	0.15	0.33	**1.00**	0.43	0.42	-0.02
G_{l25}	-0.29	**-0.64**	0.54	**0.66**	**0.61**	-0.08	-0.10	0.43	**1.00**	0.18	0.02
BR	-0.46	-0.10	0.25	0.29	0.33	0.21	0.37	0.42	0.18	**1.00**	0.10
TR	-0.11	0.33	-0.46	-0.50	0.27	-0.12	-0.22	-0.02	0.02	0.10	**1.00**

Monotonic relationships are stronger between the different questions on the survey as seen in Table 4.30 even though the calculation takes a mean over all the halls.

In Table 4.31 the subjective judgment of the participants in Gävle is correlated with the calculations of the hall instead of the measurements. However, this only reveals moderate correlation for some combinations. The highest correlation is either a negative correlation between ENS and ST_e o -0.49 or a positive correlation between DYN and G_{125} of 0.49. However, none of these trends of monotonic relations seem to be relevant for

Table 4.30: *Correlation coefficients between subjective parameters with themselves for all halls in study.*

	OAI	SUP	DYN	ENS	SPL	COL	HS	REV
OAI	**1.00**	**0.68**	**0.64**	0.43	0.52	0.36	0.24	-0.05
SUP	**0.68**	**1.00**	0.56	0.45	0.37	0.50	0.14	-0.02
DYN	**0.64**	0.56	**1.00**	0.48	0.23	0.30	0.08	0.05
ENS	0.43	0.45	0.48	**1.00**	0.20	0.41	0.32	0.00
SPL	0.52	0.37	0.23	0.20	**1.00**	0.37	-0.15	-0.30
COL	0.36	0.50	0.30	0.41	0.37	**1.00**	0.05	-0.20
HS	0.24	0.14	0.08	0.32	-0.15	0.05	**1.00**	-0.03
REV	-0.05	-0.02	0.05	0.00	-0.30	-0.20	-0.03	**1.00**

Table 4.31: *Correlation between subjective judgment and calculations in Gävle.*

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
OAI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SUP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DYN	-0.32	0.15	0.17	0.34	0.23	-0.38	-0.45	-0.34	0.49	0.28	-0.13
ENS	-0.16	0.38	-0.18	-0.01	0.00	-0.38	-0.49	0.12	0.25	0.28	-0.18
SPL	0.02	0.28	-0.25	-0.08	-0.12	0.12	0.03	-0.06	-0.05	-0.10	0.14
COL	0.23	0.13	-0.30	-0.29	-0.18	-0.31	-0.36	0.32	0.02	-0.24	-0.36
HS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
REV	-0.15	0.18	0.06	0.13	0.03	0.11	-0.08	-0.34	0.08	0.24	0.01

all halls according to Table 4.34 even though the correlation seems to have the same sign. Note that due to lack of spread in the subjective categories of OAI, SUP, and HS there is no way to calculate the correlation. This also effects the total values for these categories where the mean values from Gävle are not accounted for and do not affect the mean value.

Table 4.32: *Correlation between subjective judgment and calculations in Västerås.*

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
OAI	-0.32	-0.14	0.46	0.46	0.41	-0.43	-0.23	-0.37	0.52	0.32	0.14
SUP	-0.34	-0.19	0.45	0.45	0.50	-0.51	-0.23	-0.45	0.58	0.34	0.08
DYN	-0.03	-0.20	0.19	0.19	0.22	-0.24	-0.47	-0.35	0.34	0.03	-0.13
ENS	0.17	0.06	-0.08	-0.08	0.01	-0.02	-0.33	-0.33	0.06	-0.17	-0.13
SPL	-0.14	0.02	0.16	0.16	0.21	-0.18	-0.13	-0.17	0.20	0.14	0.20
COL	-0.06	-0.26	-0.03	-0.03	0.29	-0.31	-0.28	-0.54	0.30	0.06	0.04
HS	-0.14	-0.39	-0.10	-0.10	0.19	-0.19	0.25	0.05	0.03	0.14	-0.10
REV	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

In Västerås, there is more moderate correlation between subjective opinions and calculations according to Table 4.32 especially in the OAI and SUP category which was not present in the data for Gävle. The highest monotonic relationship is found in the correlation between SUP and G_{125} with a positive value of 0.58 and this is close to a strong correlation which has limit of 0.60. Furthermore, it seems as if G_{125} is also correlation positively with OAI with a value of 0.52 and this supports Dammerud's claim for using G_{125} as a parameter for evaluation of the acoustical climate on stages instead of BR and TR. Similarly to G_{125}, the normal G parameter has a positive correlation to OAI and SUP in Västerås which may further be an indication for the use of the parameter.

In contrast to Västerås, Jönköping has low correlation between the subjective parameters of OAI and SUP according to Table 4.33. However, Västerås has strong monotonic relations and the strongest correlation is negative between SPL and D_{50} with a value of -0.64. D_{50} also has a strong negative correlation to ENS with a value of -0.62. The high correlation values in Västerås could be due to the high response rate of 71.0 % according to Table 4.3. Since more orchestra members participate in the study, it yields more statistical results

Table 4.33: Correlation between subjective judgment and calculations in Jönköping.

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
OAI	0.41	0.32	-0.32	-0.24	-0.32	-0.06	0.19	0.07	-0.32	-0.23	-0.13
SUP	0.09	0.24	-0.15	-0.23	-0.15	-0.13	0.23	-0.02	-0.15	0.02	-0.06
DYN	0.21	0.23	-0.20	-0.20	-0.20	-0.04	0.09	-0.04	-0.20	-0.01	-0.06
ENS	0.56	0.58	-0.57	**-0.62**	-0.57	0.31	0.14	-0.08	-0.57	0.23	0.08
SPL	0.55	0.59	-0.47	**-0.64**	-0.47	0.22	0.08	-0.07	-0.47	0.24	0.11
COL	0.45	**0.63**	-0.41	-0.38	-0.41	-0.24	0.48	0.19	-0.41	-0.26	-0.07
HS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
REV	0.26	-0.02	0.07	-0.03	0.07	0.31	-0.33	0.03	0.07	-0.05	0.02

which in turn may eliminate certain extreme opinions.

Table 4.34: Correlation between subjective parameters and calculations for all halls.

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
OAI	0.05	0.09	0.07	0.11	0.05	-0.24	-0.02	-0.15	0.10	0.04	0.00
SUP	-0.12	0.03	0.15	0.11	0.18	-0.32	0.00	-0.24	0.22	0.18	0.01
DYN	-0.05	0.06	0.06	0.11	0.08	-0.22	-0.28	-0.24	0.21	0.10	-0.11
ENS	0.19	0.34	-0.28	-0.24	-0.19	-0.03	-0.23	-0.10	-0.09	0.11	-0.08
SPL	0.14	0.30	-0.19	-0.19	-0.12	0.06	-0.01	-0.10	-0.10	0.09	0.15
COL	0.21	0.17	-0.25	-0.24	-0.10	-0.29	-0.05	-0.01	-0.03	-0.15	-0.13
HS	-0.14	-0.39	-0.10	-0.10	0.19	-0.19	0.25	0.05	0.03	0.14	-0.10
REV	0.06	0.08	0.07	0.05	0.05	0.21	-0.20	-0.15	0.07	0.10	0.01

As seen in Table 4.34 there is only weak correlation between subjective judgment and calculations. However, HS is correlated with EDT by -0.39 and this may be due to the low statistical distribution of HS for both Gävle and Jönköping where the HS is marked as N/A and the only result shown in the values from Västerås. Therefore, the HS category may yield invalid correlation results.

Table 4.35: Correlation between the calculation result with itself.

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
T_{30}	**1.00**	0.49	**-0.75**	**-0.83**	**-0.83**	0.55	-0.17	0.00	**-0.81**	**-0.61**	-0.51
EDT	0.49	**1.00**	-0.51	-0.47	-0.46	0.30	0.04	-0.03	-0.42	-0.08	0.10
C_{80}	**-0.75**	-0.51	**1.00**	**0.89**	**0.82**	-0.56	-0.10	-0.02	**0.85**	0.37	0.34
D_{50}	**-0.83**	-0.47	**0.89**	**1.00**	**0.81**	**-0.64**	0.02	-0.04	**0.86**	0.30	0.30
G	**-0.83**	-0.46	**0.82**	**0.81**	**1.00**	**-0.63**	0.07	-0.03	**0.92**	0.47	0.50
LF	0.55	0.30	-0.56	**-0.64**	**-0.63**	**1.00**	-0.03	-0.14	**-0.71**	-0.12	-0.12
ST_e	-0.17	0.04	-0.10	0.02	0.07	-0.03	**1.00**	0.36	-0.18	0.01	0.37
ST_l	0.00	-0.03	-0.02	-0.04	-0.03	-0.14	0.36	**1.00**	-0.08	-0.24	0.23
G_{l25}	**-0.81**	-0.42	**0.85**	**0.86**	**0.92**	**-0.71**	-0.18	-0.08	**1.00**	0.42	0.38
BR	**-0.61**	-0.08	0.37	0.30	0.47	-0.12	0.01	-0.24	0.42	**1.00**	0.49
TR	-0.51	0.10	0.34	0.30	0.50	-0.12	0.37	0.23	0.38	0.49	**1.00**

As seen in Table 4.35, correlation between the various calculations is significantly higher than that of the objective measurements.

Table 4.36 is expected to have high values in the diagonal if the measurements and calculations correlate well to each other. However, the diagonal only has three instances of monotonic relations which are higher than the weak category. Firstly, the measured and calculated D_{50} has a strong positive correlation of 0.70. Since C_{80} and D_{50} in Table 4.29 and 4.35 have correlation values of 0.95 and 0.89 respectively, it would indicate a stronger relation between C_{80} and D_{50} in Table 4.36. However, this correlation is only moderate. This example highlights issues with these methods. Moreover, the correlation between the calculated T_{30} and the

Table 4.36: *Correlation between the calculation (rows) and measurements (columns) for Gävle, Jönköping, and Västerås.*

	T_{30}	EDT	C_{80}	D_{50}	G	LF	ST_e	ST_l	G_{l25}	BR	TR
T_{30}	0.27	0.45	-0.53	**-0.70**	-0.04	0.19	-0.16	0.03	-0.18	-0.17	**0.66**
EDT	0.07	0.32	-0.19	-0.31	0.11	0.07	0.20	0.08	0.07	0.16	0.39
C_{80}	-0.08	-0.42	0.32	0.45	0.20	-0.35	-0.15	-0.16	0.25	-0.11	-0.55
D_{50}	-0.28	-0.54	0.57	**0.70**	0.28	-0.33	0.04	-0.05	0.38	0.17	-0.52
G	-0.19	-0.27	0.42	0.56	-0.04	-0.12	-0.05	-0.26	0.18	-0.13	**-0.64**
LF	0.49	0.58	-0.51	**-0.60**	-0.45	-0.02	0.21	-0.07	**-0.64**	-0.15	0.11
ST_e	-0.17	-0.09	0.34	0.20	-0.06	0.37	0.44	-0.01	-0.23	0.09	-0.15
ST_l	0.28	0.13	-0.19	-0.12	0.22	0.31	-0.09	-0.30	0.05	0.10	0.10
G_{l25}	-0.20	-0.34	0.35	0.53	0.12	-0.26	-0.21	-0.17	0.34	-0.03	-0.55
BR	-0.27	-0.14	0.40	0.39	-0.09	0.18	0.16	0.05	0.02	0.13	**-0.62**
TR	0.22	-0.03	0.19	0.18	-0.34	0.12	0.04	-0.53	-0.22	-0.22	-0.50

measured D_{50} has a strong negative correlation of -0.70 while calculated D_{50} and the measured T_{30} have a weak correlation of only -0.28. This further supports that there is no reciprocal relation and it is difficult to establish a connection between the parameters.

4.4 MSO concert hall preference

Opinions of the MSO was collected on their own initiative and reported in a survey in the fall of 2013. Out of about 90 persons in the MSO, 39 replied in the survey which yields a response rate of about 43 percent. Responses from the survey are divided into instrument groups and are indicated in Table 4.37.

Table 4.37: *Instrument division of the respondents in the MSO study.*

Instrument	Frequency
Ba	3
Cel	4
Cl	1
Db	3
Fl	2
Hrn	2
Ob	2
Perc	1
Trb	1
Trp	1
Tub	1
Vla	6
Vl	12
Total	39

There were four question fields. The first asked what instrument they played without asking anything about the location on stage. The second field asked the musicians to mention some of the concert halls that they preferred to perform in.[3] The third field asked the musicians what they perceive as being positive in the halls mentioned in field two. The fourth field, asked if the musicians had any aspects which should be implemented in future concert halls.

Due to the location of Malmö, in the south of Sweden, and limitations in travel there are some Swedish and Danish halls which were favored. The result or the ranking order can be seen in Table 4.38.[4]

[3] Original question in Swedish: Nämn någon av de konsertsalar som du tycker bäst om att spela i. Translation: Mention some of the concert halls in which you prefer to play. Text translated by author.

[4] Halls with a frequency of one have been removed from the table.

Table 4.38: Result of top ranked halls according to musicians in the MSO.

Name	Location	Frequency
Konserthuset	Gothenburg	17
Konserthuset	Helsingborg	11
Danmarks Radio	Copenhagen (Örestad)	10
Concertgebouw	Amsterdam	9
Philiharmonie	Berlin	7
Musikverein	Vienna	6
Konserthuset	Stockholm	6
Philiharmonie	Köln	5
Danmarks Radio	Copenhagen	5
Suntory Hall	Tokyo	3
Symphony Hall	Boston	2
KKL	Luzerne	2
Konsert & Kongress	Linköping	2
Tonhalle	Zurich	2
Royal Albert Hall	London	2

The result in Table 4.38 shows that the musicians rank the Gothenburg Concert Hall as the top hall and is mentioned by 17 out of 39 musicians. According to the survey, it is possible to mention more than one hall and if multiple halls have been mentioned by the respondent, they have not been ranked or excluded.

Gothenburg's Concert Hall is closely followed by the concert hall in Helsingborg with 11 out of the 39 respondents mentioned as one of the best halls. The third ranked concert hall is the Danish Radio in Örestad which is located in Copenhagen. There are two different Danish Radio concert halls in Copenhagen and the one in Örestad is newer. Furthermore, both the Helsingborg and the new Danish Radio Concert Hall are located close to the city of Malmö where the musicians have their home venue, Gothenburg is only a few hours away as well. Less accessible halls such as the Concertgebouw in Amsterdam, the Philharmonic in Berlin, and Musikverein in Vienna follow.

Tables 4.39 and 4.40 have been realized by reading through all the comments from the 39 participants of the MSO survey and analyzing what qualities are hedged contributing to a preferred acoustical environment on stage. Since the method of collecting data was through a free flowing text, challenges have been presented in that not all participants use the same vocabulary to represent a similar contribution. It has therefore been up to the author to analyze and interpret the collected text and determine vocabulary used in the simplified ranking system.

Hear other, ensemble, and hear self are ranked highest according to Table 4.39. Warmth, clarity, and reverberation closely follows.

Table 4.40 introduces the ranking of qualities appreciated in MSO's new hall. Many of the top qualities from the top ranked halls remain at the top of the wish-list for MSO's new concert hall. However, adjustable acoustics was only mentioned by one participant in Table 4.39 and in Table 4.40 is mentioned by six participants. This may reflect the current changes in use for concert hall venues which have to adjust to various musical conditions. This shows the importance of adjustable acoustics in newly built venues and also the lack thereof in older concert halls.

Controlled brass and percussion is also an issue which is highlighted by increased rank in the concern for the new MSO hall. This could indicate a problem in the current conditions of the MSO hall.

"Enough space" was only mentioned by one participant and this is surprising due to the squeezed layout experienced by the author when measurements were performed in the hall. Especially, seating on the risers were tightly laid out with many more chairs and note stands moved during support measurements.

Table 4.39: A list of the highest ranked qualities in the top ranked hall of the MSO survey.

What qualities are appreciated in the top halls?	Number of participants
Hear other	20
Ensemble	18
Hear self	18
Warmth	9
Clarity	9
Reverberation	8
Tonal quality	7
Unity/balance between the stage and hall	7
Balance on stage	7
Ability to play softly	5
Controlled brass and per	4
Not having to press tone	3
Response of hall	3
Support	2
Control articulation	2
Nuance control	2
Listening position sound good	1
Visual contact	1
Absorption chairs same as audience	1
Adjustable acoustics	1

Table 4.40: The following table represents the amount of times each participant has mentioned a quality which they would like to have in the new hall for the MSO.

What qualities would be appreciated in the new MSO hall?	Number of participants
Hear other	19
Ensemble	12
Reverberation	11
Clarity	9
Hear self	8
Warmth	8
Balance on stage	8
Controlled brass and per	8
Adjustable acoustics	6
Nuance control	5
Unity/balance between the stage and hall	4
Tonal quality	3
Visual contact	3
Ability to play softly	2
Not having to press tone	2
Less treble	2
Wood materials	2
Less noise	2
Response of hall	1
Support	1
Control articulation	1
Listening position sound good	1
Absorption chairs same as audience	1
Enough space	1
Small hall	1

5 Conclusion

Jönköping and Västerås rank high for opinions of subjective values. Gävle on the other hand, varies greatly in the opinion in some categories with a fairly low median value. However, in OAI, SUP, and HS the ranking is unanimous due removal of outliers. Malmö has the lowest medians from the surveys, but also greater spread among the participants' replies. A closer look at DYN yielded that Malmö has difference in opinions among various sections which is an important issue to be considered in future halls. However, since there is a lack of musicians participating, correlation between instrument groups and DYN should be studied for more halls with enough participants in each instrument group. Moreover, DYN may be difficult assess due to that the directivity of the instruments are not considered during the calculations or measurements and therefore it could be difficult to find a measure which reflects the DYN. As for the coloration of sound in the different halls studied, neutral is occurring more often in the higher ranked halls while halls with a lower grade are usually more colored towards the sharp direction.

As for the objective measures, late support is similar for measurements and calculations. However, the early reflections are not consistent with larger differences between calculated and measured values for early support. LF seems to produce strange results on stage which yields unrealistic values for the measurements. It is also difficult to determine the cause of the extremely high measurements in Gävle and Malmö. Strength is uncalibrated for the measurements and therefore it is impossible to make comparisons between halls and measured and calculated values. However, it is possible to observed the difference caused by furnishing and a presence of an orchestra may further influence the result. The measurement performed in Jönköping may be faulty and should be examined carefully in order not to draw incorrect conclusions. Calculations done in CATT-Acoustic offer an alternative to check the measurements.

Generally, CATT-Acoustic values such as C_{80}, D_{50}, and TR exceed the measured values. EDT and ST_e seem to have lower calculated values than that of the corresponding measurements. This may be due to the lack of absorbing surfaces and furniture present on stage during the measurement. Measured Clarity for different positions seems to have general tendencies where the trends for calculations are less visible.

Correlation between measurements and calculations vary from not significant with some moderate and some pairs with high correlation. Correlation between subjective judgement and objective measurements do not yield any significant correlation. Therefore, it is not possible to say that there is any subjective opinions which are connected to the parameters that can be measured or calculated. In individual halls, the correlation for certain pairs are in the region of moderate to high. However, it is not possible to pin-point this to any specific reason.

The MSO survey of concert hall acoustics in general yields that hearing other, ensemble, hearing of self, reverberation, warmth, and clarity are listed as the most important traits for concert hall acoustics by musicians. These parameters have also been more or less studied in the survey which should make the survey for this thesis applicable and valid.

6 Future work

Furture work could include determining correlation in other relations than a monotonic such as a parabolic. By studying the difference between the sets of data using a t-test could also provide further evidence whether concert hall conditions are similar. Another suggestion is working with an orchestra and evaluate their opinion on other halls they play in to get a sense of how the opinion changes with the same participants. There is also a need to have higher participation and more halls to validate any trends and make them statistically significant. Moreover, there is a need to make calculations of the current hall in Malmö in order to compare with the measurements and confirm the validity. Obviously, Jönköping needs to be remeasured in order to confirm malfunctioning equipment or other reasons for the skewed outcome.

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A Appendix

Example survey

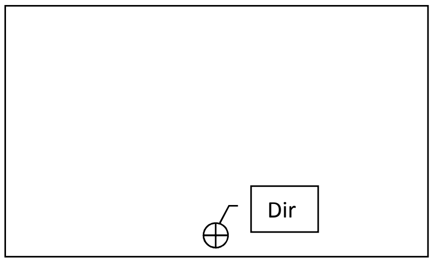
The survey is included below and Table A.1 translates the Swedish text to English. Survey was created by Norconsult and sent out to some of the halls as early as 2013. These surveys were not subject to change in this thesis.

Enkät

Enkät avseende upplevda akustiska förhållanden i Västerås konserthus

Instrument (ange även stämma): ____

Markera så gott du kan din vanligaste placering under aktuell period



Alla frågor avser egen upplevelse vid repetition och konsert med orkester.

Totalupplevelse (akustik)	Dålig	0 1 2 3 4 5 6 7 8 9 10	Bra
Rummets support/gensvar:	Dålig support Svårspelad sal	0 1 2 3 4 5 6 7 8 9 10	Bra support/ Lättspelad sal
Dynamik som uppnås i salen	Liten	0 1 2 3 4 5 6 7 8 9 10	Stor
Hör andra/ensemblekänsla	Dålig	0 1 2 3 4 5 6 7 8 9 10	Bra
Ljudnivå:	Besvärande	0 1 2 3 4 5 6 7 8 9 10	Lagom
Klangfärg*):	Färgad	0 1 2 3 4 5 6 7 8 9 10	Neutral
Hör sig själv:	För lite	-5 -4 -3 -2 -1 0 1 2 3 4 5	För mycket
Efterklang:	För torr	-5 -4 -3 -2 -1 0 1 2 3 4 5	För klangfull

*) Är klangen av orkestern mörk(basig), hård/skarp eller neutral? Ja …… Nej ……

Om Ja, i så fall vad? ……………………………………………………………………………………………

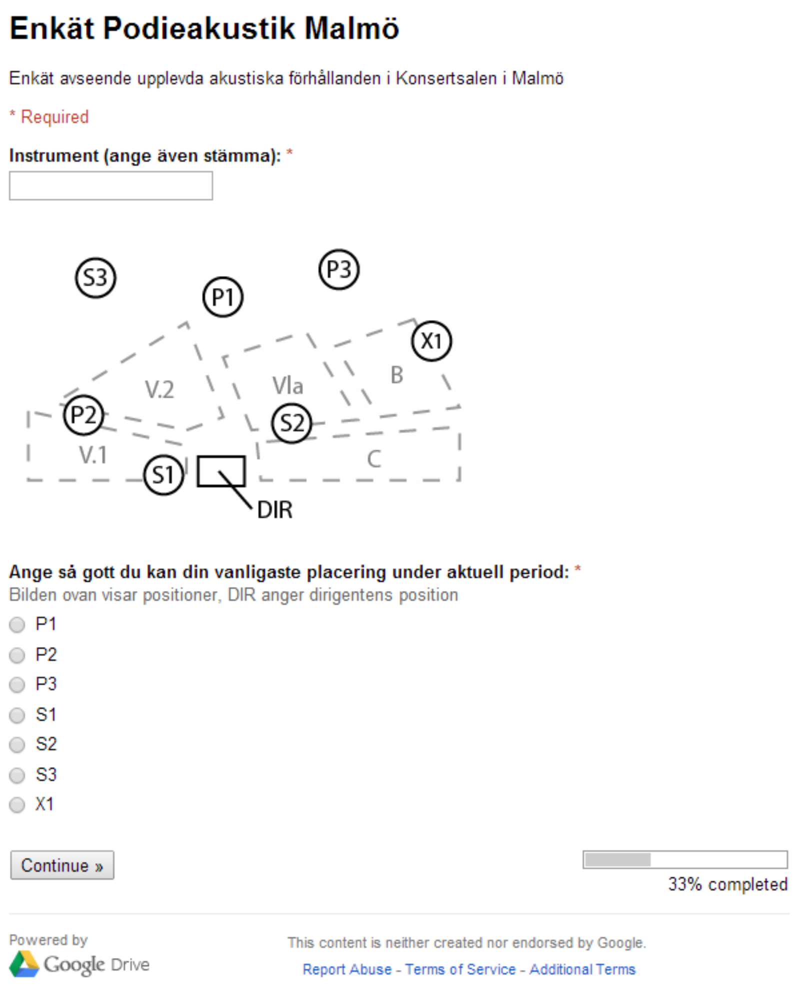
Andra kommentarer (fortsätt på baksidan), exempelvis iakttagelser ang, placering relativt annat instrument, spelat verk etc, storlek på orkester.

Namn:

Table A.1: *Simplified translation of survey from Swedish to English.*

Swedish	English	Abbreviation	Minimum	Maximum
Totalupplevelese (akustik)	Overall acoustic impression	OAI	Bad	Good
Rummets support	Room's support	SUP	Bad support	Good support
Dynamik som uppnås i salen	Hall's dynamics	DYN	Small	Large
Ensembelkänsla	Feeling of ensemble	ENS	Bad	Good
Ljudnivå	Sound Pressure Level	SPL	Bothersome	Adequate
Klängfärg	Tone coloration	COL	Colored	Neutral
Hör sig själv	Ability to hear oneself	HS	Too little	Too much
Efterklang	Reverberation	REV	Too dry	Too reverberant

However, Malmö requested an online survey in order to gain more responses and their survey was created through Google Drive which has a survey option. Figure A.1 shows that the online survey made it possible to require certain answers, unlike a paper survey where the musician can choose not to answer a question. Furthermore, in the paper survey positions were indicated by the musician drawing the positions from the conductors placement and the author having to guess where the actual position is located. In some cases, this was a difficult task due to the proportions and no indication of instrument groups. However, by letting the musicians select the appropriate location themselves with a better reference, the translation was improved.


Enkät Podieakustik Malmö

Enkät avseende upplevda akustiska förhållanden i Konsertsalen i Malmö

* Required

Instrument (ange även stämma): *

Ange så gott du kan din vanligaste placering under aktuell period: *

Bilden ovan visar positioner, DIR anger dirigentens position

- P1
- P2
- P3
- S1
- S2
- S3
- X1

Continue »

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Figure A.1: Malmö survey with a different way of indicating musicians position.

Figure A.2 shows the layout of some of the ranking questions. Note that the question related to the tone coloration or COL (klangfärg) was moved to after the ranking. This decision was made due to that the analyzed paper surveys got low replies and according to the author, moving it up to the ranking made more sense. Moreover, due to the settings in the survey the scale for HS and REV could not be set to range between -5 to 5, only values of 0 to 10 could be applied. Consequently, the scale for HS and REV was adjusted and a warning below indicates that 5 is a neutral value. Note, all the ranking questions were required to answer, the reason for this is that translating the survey from a single paper to an online version makes it longer and not as comprehensible as the paper version. Therefore the survey was divided into 3 pages and some question required to answer in order not to accidentally skip a question. On the other hand, forcing the participant to answer a question might skew the collected with a data which does not reflect the respondents opinion.


Ljudnivå *
0 1 2 3 4 5 6 7 8 9 10
Besvärande Lagom

Klangfärg *
0 1 2 3 4 5 6 7 8 9 10
Färgad Neutral

Är klangfärgen av orkestern mörk(basig), hård/skarp eller neutral? *
Ja
Nej

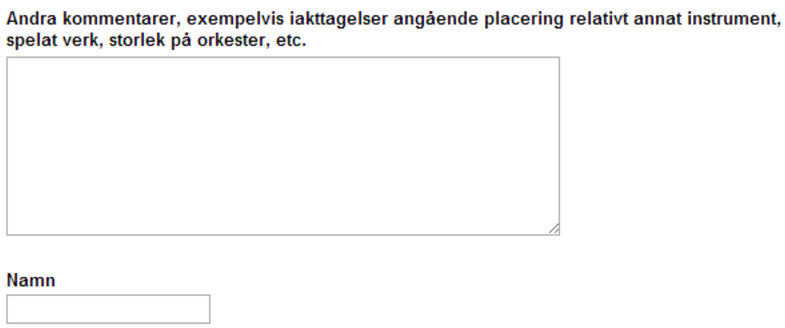
Om Ja, i så fall vad?

Hör sig själv *
OBS! ett värde av 5 anses neutralt
0 1 2 3 4 5 6 7 8 9 10
För lite För mycket

Efterklang *
OBS! ett värde av 5 anses neutralt
0 1 2 3 4 5 6 7 8 9 10
För torr För klangfull

Figure A.2: Malmö survey with example of ranking questions.

Figure A.3 shows the optional comment which might be easier to fill in on a computer than writing by hand on the paper survey. The name field was left optional due to that the participants should not feel forced to reveal their identity although instrument and instrument harmony might already pinpoint a specific person in the orchestra.


Andra kommentarer, exempelvis iakttagelser angående placering relativt annat instrument, spelat verk, storlek på orkester, etc.

Namn

Figure A.3: Malmö survey with optional text.

B Appendix

B.1 Beranek's abbreviations for concert halls

List is from Beranek's *Concert Halls and Opera Houses: Music, Acoustics, and Architecture* on page 496 and are refereed to in illustrations done by Beranek. (Beranek, 2004, p. 496)

VM	Vienna, Grosser Musikvereinssaal
BO	Boston, Symphony Hall
BA	Buenos Aires, Teatro Colón (Concert Shell)
BZ	Berlin, Konzerthaus (Schauspielhaus)
AM	Amsterdam, Concertgebouw
TN	Tokyo, Tokyo Opera City TOC Concert Hall
ZT	Zurich, Grosser Tonhallesaal
NY	New York, Carnegie Hall
BC	Basel, Stadt-Casino
CW	Cardiff, St. David's Hall
DA	Dallas, McDermott/Meyerson Hall
BN	Bristol, Colston Hall
SO	Lenox, Seiji Ozawa Hall
CM	Costa Mesa, Segerstrom
SL	Salt Lake City, Abravanel Symphony Hall
BP	Berlin Philharmonie
TS	Tokyo, Suntory Hall
TB	Tokyo, Bunka Kaikan (Orchestra Shell)
BR	Brussels, Palais des Beaux-Arts (Renovated)
BM	Baltimore, Meyerhoff Symphony Hall
21 to 39	*Bonn, Beethovenhalle* *Chicago, Civic Center* *Chicago, Orchestra Hall (br)* *Christchurch, Town Hall* *Cleveland, Severance Hall (br)* *Gothenburg, Konserthus* *Jerusalem, Binyanei Ha'Oomah* *Kyoto, Concert Hall* *Leipzig, Gewandhaus* *Lenox, Tanglewood Music Shed* *Munich, Philharmonie Am Gasteig* *Osaka, Symphony Hall* *Rotterdam, De Doelen Concertgebouw* *Tokyo, Metropolitan Art Space* *Tokyo, Orchard Hall, Bunkamura* *Toronto, Roy Thompson Hall (br)* *Vienna, Konzerthaus (br)* *Washington, JFK Concert Hall (br)* *Washington, JFK Opera House (set)*
SA	Salzburg, Festspielhaus
ST	Stuttgart, Liederhalle, Grosser Saal
AF	New York, Avery Fisher Hall
CR	Copenhagen, Radiohuset, Studio 1
EB	Edinburgh, Usher Hall (br)
GL	Glasgow, Royal Concert Hall (br)
LF	London, Royal Festival Hall (br)
LV	Liverpool, Philharmonic Hall (br)
MA	Manchester, Free Trade Hall (Replaced)
PP	Paris, Salle Pléyel (br)
ED	Edmonton, No. Alberta Jubilee Auditorium (br)
MP	Montreal, Salle Wilfrid-Pelletier (br)
TK	Tokyo, NHK Hall (3,677 seats)
SH	Sydney, Opera House Concert Hall (br)
SF	San Francisco, Davies Symphony Hall (br)
TE	Tel Aviv, Fredric R. Mann Auditorium (br)
LB	London, Barbican, Large Concert Hall (br)
BU	Buffalo, Kleinhans Music Hall (br)
LA	London, Royal Albert Hall (5,080 seats) (br)

Note: (br) means before recent renovations. These halls may have greatly changed acoustics since renovations.

C Appendix

C.1 Architectural plans

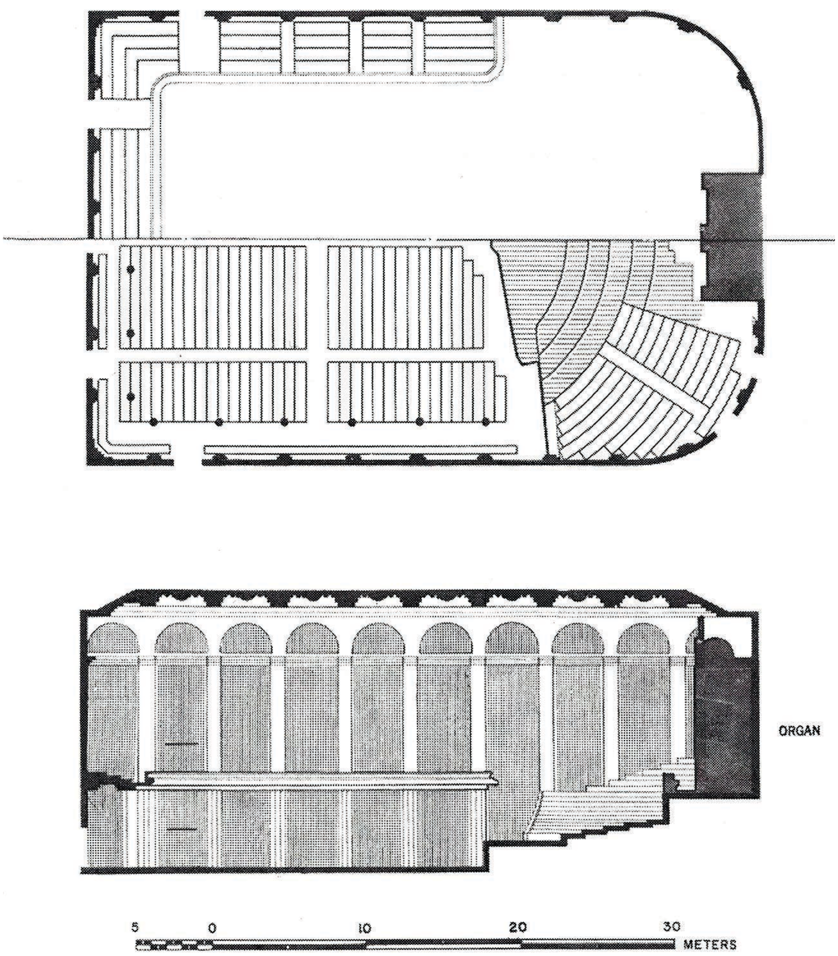


Figure C.1: Plan and section of the Amsterdam Concertgebouw. (Beranek, 2004, p. 427)

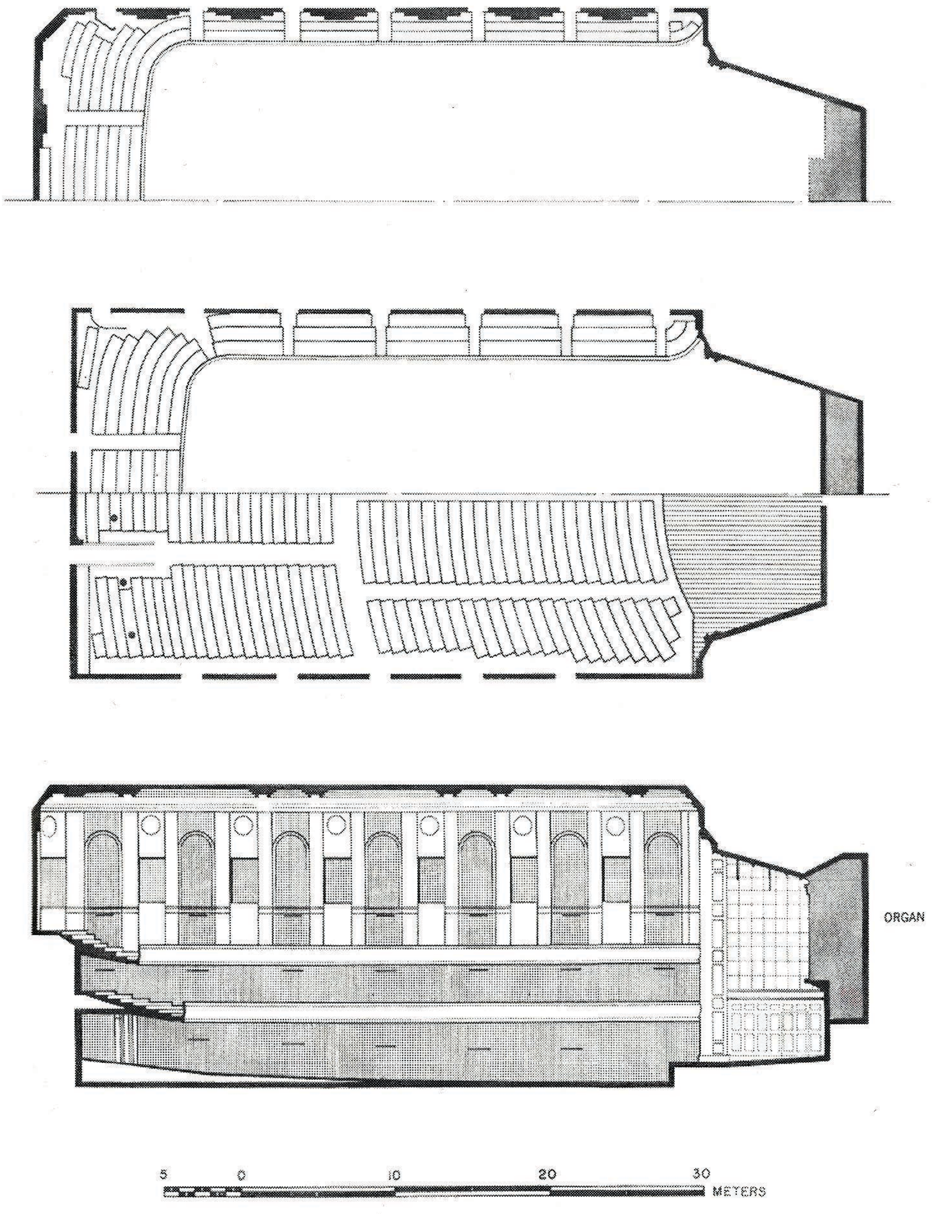


Figure C.2: Plan and section of the Boston Symphony Hall. (Beranek, 2004, p. 49)

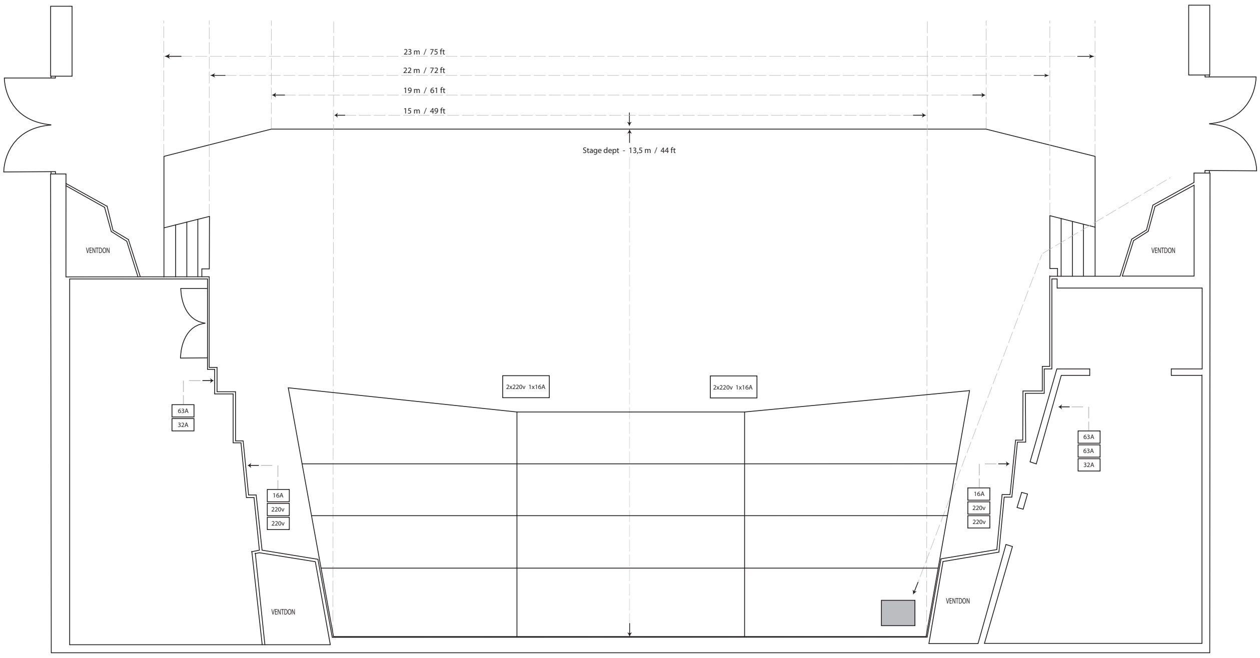


Figure C.3: Plan of Malmö's concert hall stage showing placement of risers and dimensions. MSO (n.d.)

D Appendix

D.1 Computer models

Table D.1: Surface material data for VM in octave bands from 125 Hz to 4 kHz is displayed to illustrate absorptive and diffusive properties of materials in CATT-Acoustic models.

Type of material	Absorption coefficients	Scattering
Audience	53 63 76 83 86 85	40 50 60 80 80 80
Carpet vertical	2 6 14 38 60 65	
Ceiling	31 28 18 15 12 12	estimate(0,1)
Decor	1 1 2 2 3 3	estimate(0,1)
Doors	14 10 6 8 8 8	20 17 15 13 11 10
Floor	1 1 1 1 2 2	20 17 15 13 11 10
Glas covered with panel material	14 10 6 8 8 8	20 17 15 13 11 10
Open	99 99 99 99 99 99	
Orchestra	30 40 50 50 50 50	40 50 60 80 80 80
Organ	10 10 10 10 10 10	estimate(0,15)
Panel	13 12 10 6 8 9	20 17 15 13 11 10
Pillars	1 1 1 1 2 2	estimate(0,3) ¿
Podium	30 20 20 17 15 10	20 17 15 13 11 10
Statues	10 10 10 10 10 10	20 17 15 13 11 10
Steps	1 1 1 1 2 2	estimate(0,27)
Window frame	1 1 2 2 3 3	estimate(0,1)

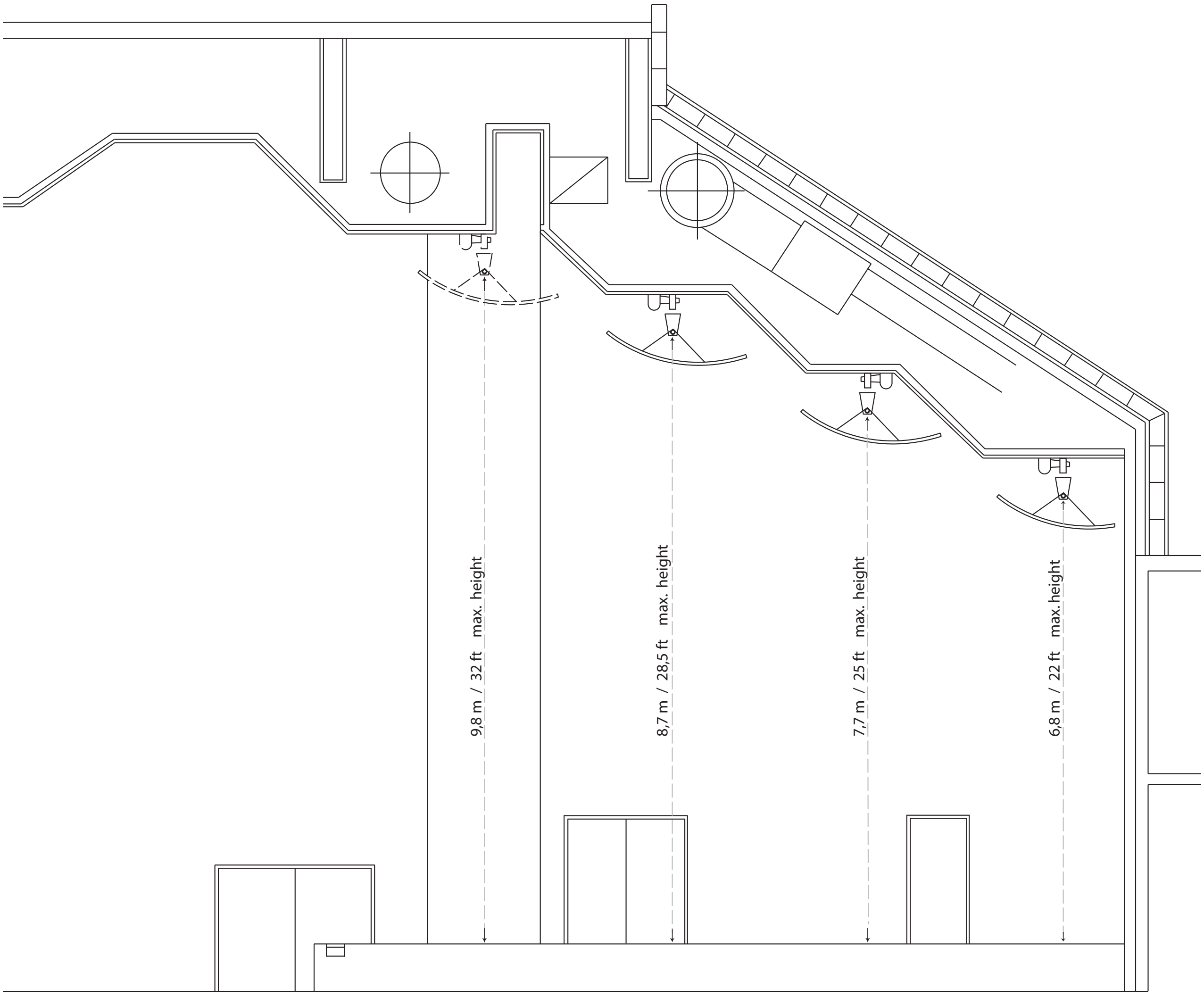


Figure C.4: Section of Malmö's concert hall stage showing reflectors height construction of ceiling. MSO (n.d.)

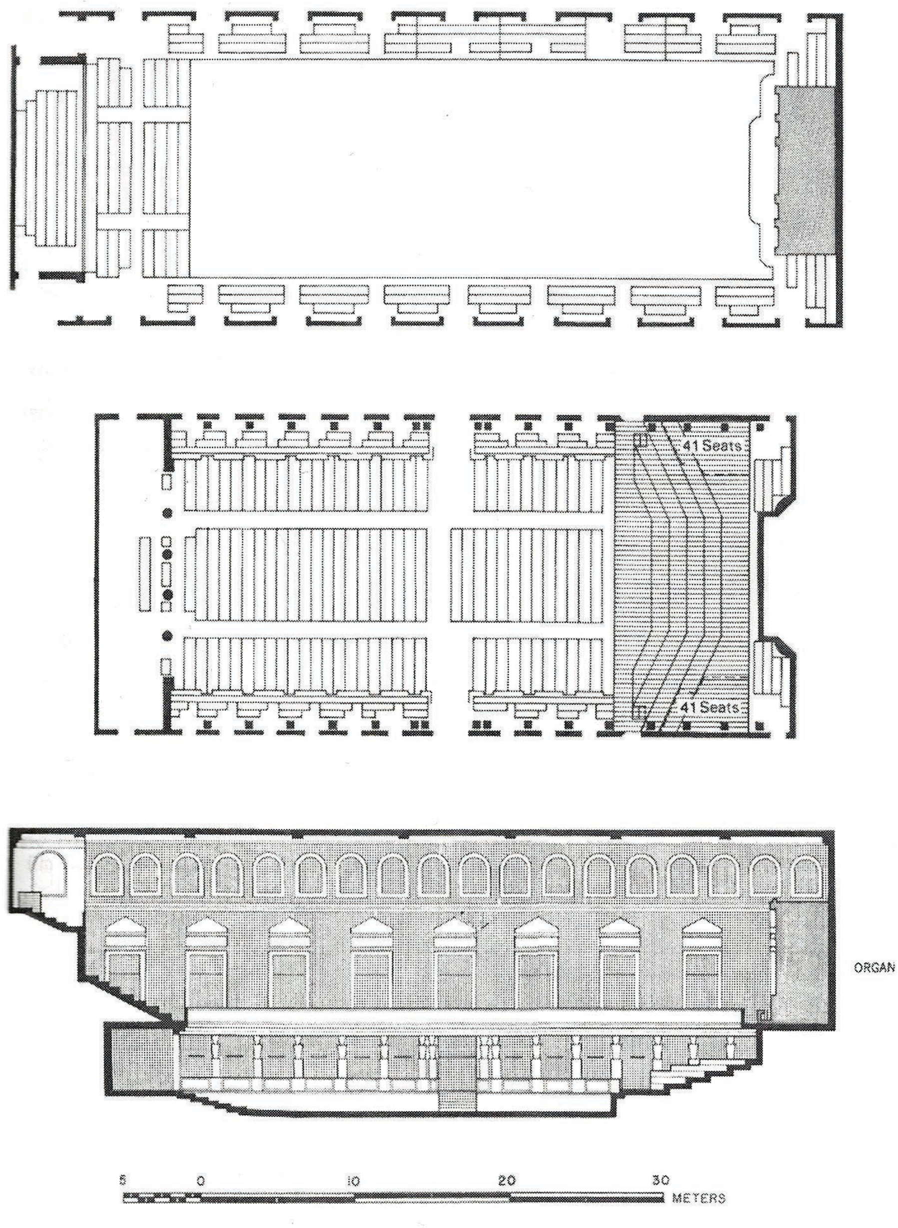


Figure C.5: Plan and section of the Vienna Grosser Musikvereinsaal. (Beranek, 2004, p. 175)

E Appendix

Spearman calculation in VBA

```
Sub SpearmanTable()
'
'*************************************************************************************
'       Function     Calculate the Spearman's Coefficient for a table using the Spearman sub
'
'*************************************************************************************
'
'
Application.ScreenUpdating = False
Application.DisplayAlerts = False
'Active cell pick out row and col number
Sheets("SpearmanTables").Activate
Dim row As Integer, col As Integer
row = ActiveCell.row
col = ActiveCell.Column
'Pick out name one above
Dim HallName As String, ColType As String, RowType As String
HallName = Cells(row - 1, col).Value
ColType = Cells(row - 1, col + 1).Value
RowType = Cells(row, col - 1).Value
'Find how many subjective parameters
Dim NrRowParam As Integer, NrColParam As Integer
NrRowParam = 0
Cells(row + 1, col).Select
If IsEmpty(ActiveCell) = False Then
    Do
        NrRowParam = NrRowParam + 1
        'move down
        ActiveCell.Offset(1, 0).Select
    Loop Until IsEmpty(ActiveCell) = True
Else
    'Do nothing
End If
'Find how many objective parameters
NrColParam = 0
Cells(row, col + 1).Select
If IsEmpty(ActiveCell) = False Then
    Do
        NrColParam = NrColParam + 1
        'move down
        ActiveCell.Offset(0, 1).Select
    Loop Until IsEmpty(ActiveCell) = True
Else
    'Do nothing
End If
Dim RowParam As String, ColParam As String, Spear_r As String, AbsSpear_r As Double
'Start with first subjective parameter and loop overall
For j = 1 To NrRowParam
    RowParam = Cells(row + j, col).Value
    'Inside subjective parameter loop over objective parameter
    For jj = 1 To NrColParam
        ColParam = Cells(row, col + jj).Value
        'Run Spearman subroutine to get the correlation coefficient r
        Sheets("SPRC_diff").Activate
        Cells(1, 2).Value = HallName
        Cells(2, 2).Value = RowParam
        Cells(2, 3).Value = ColParam
        Cells(3, 2).Value = RowType
        Cells(3, 3).Value = ColType
        Application.ScreenUpdating = True
        Application.DisplayAlerts = True
        Spearman_diff
        Application.ScreenUpdating = False
        Application.DisplayAlerts = False
        Spear_r = Cells(7, 15).Value
        'Activate the correct sheet
        Sheets("SpearmanTables").Activate
        'FIX UNDERLINE FOR N/A
        'CODE SHOULD REST TYPE OF FONT FOR ALL CELLS IN TABLE
        'Check if N/A otherwise take the absolute value of the spearman coe.
        If Spear_r = "N/A" Then
            'Do nothing
        Else
            AbsSpear_r = Abs(Spear_r)
```

```
        End If
        'Weak monotonic relation
        If IsNumeric(AbsSpear_r) And AbsSpear_r >= 0 And AbsSpear_r <= 0.39 Then
            Cells(row + j, col + jj).Interior.ColorIndex = xlColorIndexNone
            Cells(row + j, col + jj).Font.Underline = False
            Cells(row + j, col + jj).Font.Bold = False
            ' Write r in table
            Cells(row + j, col + jj).Value = Spear_r
        End If
        'Moderate relation
        If AbsSpear_r >= 0.4 And AbsSpear_r <= 0.59 Then
            Cells(row + j, col + jj).Interior.Color = RGB(255, 255, 204)
            Cells(row + j, col + jj).Font.Underline = True
            Cells(row + j, col + jj).Font.Bold = False
            ' Write r in table
            Sheets("SpearmanTables").Activate
            Cells(row + j, col + jj).Value = Spear_r
        End If
        'Strong relation
        If AbsSpear_r >= 0.6 And AbsSpear_r <= 0.79 Then
            Cells(row + j, col + jj).Interior.Color = RGB(255, 204, 153)
            Cells(row + j, col + jj).Font.Bold = True
            Cells(row + j, col + jj).Font.Underline = False

            ' Write r in table
            Sheets("SpearmanTables").Activate
            Cells(row + j, col + jj).Value = Spear_r
        End If
        'Very strong relation
        If AbsSpear_r >= 0.8 And AbsSpear_r <= 1 Then
            Cells(row + j, col + jj).Interior.Color = RGB(255, 153, 153)
            Cells(row + j, col + jj).Font.Underline = True
            Cells(row + j, col + jj).Font.Bold = True

            ' Write r in table
            Sheets("SpearmanTables").Activate
            Cells(row + j, col + jj).Value = Spear_r
        End If
        If Spear_r = "N/A" Then
            Cells(row + j, col + jj).Interior.Color = RGB(204, 229, 255)
            Cells(row + j, col + jj).Font.Underline = False
            Cells(row + j, col + jj).Font.Bold = False

            ' Write r in table
            Sheets("SpearmanTables").Activate
            Cells(row + j, col + jj).Value = Spear_r
        Else
        End If
    Next jj
Next j
Application.ScreenUpdating = True
Application.DisplayAlerts = True
End Sub



Sub Spearman_diff()
'
'*************************************************************************************
'       Function    Calculate the Spearman's Coefficient
'
'*************************************************************************************
'
'
Application.ScreenUpdating = False
Application.DisplayAlerts = False
'Add workpath otherwise it does not find the measurement excel sheet
Workbooks.Open (ThisWorkbook.Path & "\" & "Measurements.xlsx")
ActiveWorkbook.RunAutoMacros xlAutoOpen
'Add workpath otherwise it does not find the catt calc excel sheet
Workbooks.Open (ThisWorkbook.Path & "\" & "CATT_calc.xlsm")
ActiveWorkbook.RunAutoMacros xlAutoOpen
'Open the Spearman's Coefficient sheet
Workbooks("Surveys.xlsm").Activate
Sheets("SPRC_diff").Activate
'Dimension parameters which is extracted from the SPRC_diff sheet
Dim HallName As String, RowParam As String, ColParam As String, RowType As String, ColType As ↩
    String
'Pick out the name of the hall
Cells(1, 2).Select
HallName = ActiveCell.Value
'Pick out the row parameter
ActiveCell.Offset(1, 0).Select
RowParam = ActiveCell.Value
```

```
'Pick out the column parameter
ActiveCell.Offset(0, 1).Select
ColParam = ActiveCell.Value
'Pick out the types of the two different parameters
'These can vary between Sub, Obj, and hopefully Calc
ActiveCell.Offset(1, 0).Select
ColType = ActiveCell.Value
ActiveCell.Offset(0, -1).Select
RowType = ActiveCell.Value
'Go to the hall's survey sheet
Sheets(HallName & "_Survey").Activate
'Dimension a counter in order to count how many musicians are in the result
Dim NrMus As Integer
NrMus = 0
'Count how many musicians participated in the the hall
Cells(1, 3).Select
If IsEmpty(ActiveCell) = False Then
    Do
        NrMus = NrMus + 1
        'move down
        ActiveCell.Offset(0, 1).Select
    Loop Until IsEmpty(ActiveCell) = True
Else
    'Do nothing
End If
Sheets("SPRC_diff").Activate
'CLEAR SPRC_diff sheet from old data
Range(Cells(6, 1), Cells(5 + 2 * NrMus, 13)).Clear
'Go back to the hall survey sheet
'Select the positions for each musician and COPY it
Sheets(HallName & "_Survey").Activate
Range(Cells(5, 3), Cells(5, 3 + NrMus - 1)).Select
Selection.Copy
'Perform a special paste of the Positions where the data is transformed in the SPRC_diff
Sheets("SPRC_diff").Activate
Cells(6, 1).Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=True
'Go to the hall's survey sheet
Sheets(HallName & "_Survey").Activate
'IF THE ROWTYPE IS SUB
Dim Param As String, Param_pos_row As Integer
If RowType = "Sub" Then
    Param = RowParam
    'Find what row the subjective parameter is located on
    Param_pos_row = Range("B:B").Find(Param, Range("B1"), xlValues, xlWhole, xlByColumns, xlNext).↩
        row
    Param_pos_row = Param_pos_row + 43
'SELECT the Subjective data for att musicians and COPY it!
    Range(Cells(Param_pos_row, 3), Cells(Param_pos_row, 3 + NrMus - 1)).Select
    Selection.Copy
    'Perform a special paste where the data is transformed in the SPRC_diff
    Sheets("SPRC_diff").Activate
    Cells(6, 2).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=↩
        True
Else
    'Do Nothing
End If
'IF THE ROWTYPE IS OBJ
Dim j As Integer, PosMus As String, PosMus_row As Integer, PosMus_col As Integer, ObjVal As String
If RowType = "Obj" Then
'GET ALL THE OBJECTIVE DATA ACCORDING TO THE POSITIONS OF THE MUSICIANS
    For j = 1 To NrMus
        'open the correct sheet in surveys
        Sheets("SPRC_diff").Activate
        'get the musicians position
        PosMus = Cells(5 + j, 1).Value
        'go to measurement and select the correct sheet
        Workbooks("Measurements.xlsx").Activate
        Sheets(HallName & "_" & RowParam).Activate
        'locate the row where objective measure position is
        PosMus_row = Columns(1).Find(PosMus, Range("A1"), xlValues, xlWhole, xlByColumns, xlNext).↩
            row
        PosMus_row = PosMus_row + 1
        'look for "avg" in row and find the column number
        PosMus_col = Rows(PosMus_row).Find("avg", Cells(PosMus_row, 1), xlValues, xlWhole, ↩
            xlByRows, xlNext).Column
        If IsNumeric(Cells(PosMus_row + 1, PosMus_col).Value) Then
            'Get the objective value from the measurement sheet
            ObjVal = Cells(PosMus_row + 1, PosMus_col).Value
        Else
            ' If there is no numeric value set ObjVal as "N"
            ObjVal = "N"
            'ObjVal = Cells(PosMus_row + 1, PosMus_col).Value = "N"
```

```
        End If
        'Go to the surveys workbook
        Workbooks("Surveys.xlsm").Activate
        Cells(5 + j, 2).Value = ObjVal
    Next j
Else
    'Do Nothing
End If
'IF THE COLTYPE IS OBJ
If ColType = "Obj" Then
'GET ALL THE OBJECTIVE DATA ACCORDING TO THE POSITIONS OF THE MUSICIANS
    For j = 1 To NrMus
        'open the correct sheet in surveys
        Sheets("SPRC_diff").Activate
        'get the musicians position
        PosMus = Cells(5 + j, 1).Value
        'go to measurement and select the correct sheet
        Workbooks("Measurements.xlsx").Activate
        Sheets(HallName & "_" & ColParam).Activate
        'locate the row where objective measure position is
        PosMus_row = Columns(1).Find(PosMus, Range("A1"), xlValues, xlWhole, xlByColumns, xlNext).↩
            row
        PosMus_row = PosMus_row + 1
        'look for "avg" in row and find the column number
        PosMus_col = Rows(PosMus_row).Find("avg", Cells(PosMus_row, 1), xlValues, xlWhole, ↩
            xlByRows, xlNext).Column
        If IsNumeric(Cells(PosMus_row + 1, PosMus_col).Value) Then
            'Get the objective value from the measurement sheet
            ObjVal = Cells(PosMus_row + 1, PosMus_col).Value
        Else
            ' If there is no numeric value set ObjVal as "N"
            ObjVal = "N"
        End If
        'Go to the surveys workbook
        Workbooks("Surveys.xlsm").Activate
        Cells(5 + j, 3).Value = ObjVal
    Next j
Else
    'Do Nothing
End If
'IF CALC
'IF THE ROWTYPE IS CALC
Dim PosStart_row As Integer, CalcVal As String, RowParam_sheet As String
If RowType = "Calc" Then
'GET ALL THE OBJECTIVE DATA ACCORDING TO THE POSITIONS OF THE MUSICIANS
    For j = 1 To NrMus
        'open the correct sheet in surveys
        Sheets("SPRC_diff").Activate
        'get the musicians position
        PosMus = Cells(5 + j, 1).Value
        'go to measurement and select the correct sheet
        Workbooks("CATT_calc.xlsm").Activate
        'If rowparam is BR or TR then the T30 sheet should be opened
        If RowParam = "BR" Or RowParam = "TR" Then
            RowParam_sheet = "T30"
            Sheets(HallName & "_General_" & RowParam_sheet & "_con").Activate
        Else
            'If rowparam is ST... then the ST sheet should be opened
            If RowParam = "ST_e" Or RowParam = "ST_l" Then
                RowParam_sheet = "ST"
                Sheets(HallName & "_" & RowParam_sheet & "_con").Activate
            Else
                If RowParam = "G125" Then
                    RowParam_sheet = "G"
                    Sheets(HallName & "_General_" & RowParam_sheet & "_con").Activate
                Else
                    'This is for normal open
                    RowParam_sheet = RowParam
                    Sheets(HallName & "_General_" & RowParam_sheet & "_con").Activate
                End If
            End If
        End If
        'locate the row where objective measure position is
        PosStart_row = Columns(2).Find("Positions", Range("B1"), xlValues, xlWhole, xlByColumns, ↩
            xlNext).row
        PosMus_row = Columns(2).Find(PosMus, Cells(PosStart_row, 2), xlValues, xlWhole, ↩
            xlByColumns, xlNext).row
        If RowParam_sheet = "ST" Then
            'Do nothing
        Else
            'look for "Average" in row and find the column number
            PosMus_col = Rows(PosStart_row).Find("Average", Cells(PosStart_row, 1), xlValues, ↩
                xlWhole, xlByRows, xlNext).Column
        End If
```

```
            If RowParam = "BR" Then
            PosMus_col = Rows(PosStart_row).Find("BR", Cells(PosStart_row, 1), xlValues, xlWhole, ↩
                xlByRows, xlNext).Column
            End If
            If RowParam = "TR" Then
            PosMus_col = Rows(PosStart_row).Find("TR", Cells(PosStart_row, 1), xlValues, xlWhole, ↩
                xlByRows, xlNext).Column
            End If
            If RowParam = "ST_e" Then
            PosMus_col = Rows(PosStart_row).Find("ST_early", Cells(PosStart_row, 1), xlValues, xlWhole↩
                , xlByRows, xlNext).Column
            End If
            If RowParam = "ST_l" Then
            PosMus_col = Rows(PosStart_row).Find("ST_late", Cells(PosStart_row, 1), xlValues, xlWhole,↩
                 xlByRows, xlNext).Column
            End If
            If RowParam = "G125" Then
            PosMus_col = Rows(PosStart_row).Find("G125", Cells(PosStart_row, 1), xlValues, xlWhole, ↩
                xlByRows, xlNext).Column
            End If
            If IsNumeric(Cells(PosMus_row, PosMus_col).Value) Then
                'Get the objective value from the measurement sheet
                CalcVal = Cells(PosMus_row, PosMus_col).Value
            Else
                ' If there is no numeric value set ObjVal as "N"
                CalcVal = Cells(PosMus_row, PosMus_col).Value = "N"
            End If
            'Go to the surveys workbook
            Workbooks("Surveys.xlsm").Activate
            Cells(5 + j, 2).Value = CalcVal
        Next j
    Else
        'Do Nothing
    End If
    'IF THE COLTYPE IS CALC
    If ColType = "Calc" Then
    'GET ALL THE OBJECTIVE DATA ACCORDING TO THE POSITIONS OF THE MUSICIANS
        For j = 1 To NrMus
            'open the correct sheet in surveys
            Sheets("SPRC_diff").Activate
            'get the musicians position
            PosMus = Cells(5 + j, 1).Value
            'go to measurement and select the correct sheet
            Workbooks("CATT_calc.xlsm").Activate

            'If rowparam is BR or TR then the T30 sheet should be opened
            If ColParam = "BR" Or ColParam = "TR" Then
                ColParam_sheet = "T30"
                Sheets(HallName & "_General_" & ColParam_sheet & "_con").Activate
            Else
                'If rowparam is ST... then the ST sheet should be opened
                If ColParam = "ST_e" Or ColParam = "ST_l" Then
                    ColParam_sheet = "ST"
                    Sheets(HallName & "_" & ColParam_sheet & "_con").Activate
                Else
                    If ColParam = "G125" Then
                        ColParam_sheet = "G"
                        Sheets(HallName & "_General_" & ColParam_sheet & "_con").Activate
                    Else
                        'This is for normal open
                        ColParam_sheet = ColParam
                        Sheets(HallName & "_General_" & ColParam_sheet & "_con").Activate
                    End If
                End If
            End If
            'locate the row where objective measure position is
            PosStart_row = Columns(2).Find("Positions", Range("B1"), xlValues, xlWhole, xlByColumns, ↩
                xlNext).row
            PosMus_row = Columns(2).Find(PosMus, Cells(PosStart_row, 2), xlValues, xlWhole, ↩
                xlByColumns, xlNext).row
            If ColParam_sheet = "ST" Then
                'Do nothing
            Else
                'look for "Average" in row and find the column number
                PosMus_col = Rows(PosStart_row).Find("Average", Cells(PosStart_row, 1), xlValues, ↩
                    xlWhole, xlByRows, xlNext).Column
            End If
            If ColParam = "BR" Then
            PosMus_col = Rows(PosStart_row).Find("BR", Cells(PosStart_row, 1), xlValues, xlWhole, ↩
                xlByRows, xlNext).Column
            End If
            If ColParam = "TR" Then
            PosMus_col = Rows(PosStart_row).Find("TR", Cells(PosStart_row, 1), xlValues, xlWhole, ↩
                xlByRows, xlNext).Column
```

```
            End If
            If ColParam = "ST_e" Then
            PosMus_col = Rows(PosStart_row).Find("ST_early", Cells(PosStart_row, 1), xlValues, xlWhole↩
                , xlByRows, xlNext).Column
            End If
            If ColParam = "ST_l" Then
            PosMus_col = Rows(PosStart_row).Find("ST_late", Cells(PosStart_row, 1), xlValues, xlWhole,↩
                 xlByRows, xlNext).Column
            End If
            If ColParam = "G125" Then
            PosMus_col = Rows(PosStart_row).Find("G125", Cells(PosStart_row, 1), xlValues, xlWhole, ↩
                xlByRows, xlNext).Column
            End If
            If IsNumeric(Cells(PosMus_row, PosMus_col).Value) Then
                'Get the objective value from the measurement sheet
                CalcVal = Cells(PosMus_row, PosMus_col).Value
            Else
                ' If there is no numeric value set ObjVal as "N"
                CalcVal = Cells(PosMus_row, PosMus_col).Value = "N"
            End If
            'Go to the surveys workbook
            Workbooks("Surveys.xlsm").Activate
            Cells(5 + j, 3).Value = CalcVal
        Next j
    Else
        'Do Nothing
    End If
    'IF THE COLTYPE IS SUB
    If ColType = "Sub" Then
        'Go to the hall's survey sheet
        Sheets(HallName & "_Survey").Activate
        Param = ColParam
        'Find what row the subjective parameter is located on
        Param_pos_row = Range("B:B").Find(Param, Range("B1"), xlValues, xlWhole, xlByColumns, xlNext).↩
            row
        Param_pos_row = Param_pos_row + 43

    'SELECT the Subjective data for att musicians and COPY it!
        Range(Cells(Param_pos_row, 3), Cells(Param_pos_row, 3 + NrMus - 1)).Select
        Selection.Copy

        'Perform a special paste where the data is transformed in the SPRC_diff
        Sheets("SPRC_diff").Activate
        Cells(6, 3).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=↩
            True
    Else
        'Do Nothing
    End If
    'Close the measurement workbook
    Workbooks("Measurements.xlsx").Close SaveChanges:=False
    'Close the measurement workbook
    Workbooks("CATT_calc.xlsm").Close SaveChanges:=False
    'DELETE all parameters which are not numeric and the counter part
    For j = 1 To NrMus
    If IsNumeric(Cells(5 + j, 2).Value) Then
        'Let it be
    Else
        'Cells(5 + j, 1).Clear
        Cells(5 + j, 2).Value = "N"
        Cells(5 + j, 3).Value = "N"
    End If
    If IsNumeric(Cells(5 + j, 3).Value) Then
        'Let it be
    Else
        'Cells(5 + j, 1).Clear
        Cells(5 + j, 2).Value = "N"
        Cells(5 + j, 3).Value = "N"
    End If
    Next j
    'RANK THE SUBJECTIVE VALUES
    'if the same value is repeated many times then the value for at cells is the average
    Dim r As Double, C As Double, A As Double, MusX As Integer
    MusX = 0
    'Rank the Subjective parameters
    For j = 1 To NrMus
        If IsNumeric(Cells(5 + j, 2).Value) And IsNumeric(Cells(5 + j, 3).Value) Then
            r = WorksheetFunction.Rank(Cells(5 + j, 2).Value, Range(Cells(5 + 1, 2), Cells(5 + NrMus, ↩
                2)))
            C = WorksheetFunction.CountIf(Range(Cells(5 + 1, 2), Cells(5 + NrMus, 2)), Cells(5 + j, 2)↩
                .Value)
            A = WorksheetFunction.Average(r, r + C - 1)
            A = NrMus + 1 - A
            'Write the rank to column 5 i the SPRC_diff sheet
```

```
            Cells(5 + j, 5) = A
        Else
        MusX = MusX + 1
        End If
    Next j
    'Calculate the mean subjective rank
    Cells(NrMus + 6, 5).Value = WorksheetFunction.Average(Range(Cells(6, 5), Cells(5 + NrMus, 5)))
    'Calculate the Std subjective rank
    Cells(NrMus + 7, 5).Value = WorksheetFunction.StDev(Range(Cells(6, 5), Cells(5 + NrMus, 5)))
    'The cell next to N should have the number of musicians or the amount of data points.
    Cells(5, 15).Select
    ActiveCell.Value = NrMus - MusX
    'Rank the Objective parameters
    For j = 1 To NrMus
        If IsNumeric(Cells(5 + j, 2).Value) And IsNumeric(Cells(5 + j, 3).Value) Then
            r = WorksheetFunction.Rank(Cells(5 + j, 3).Value, Range(Cells(5 + 1, 3), Cells(5 + NrMus, ↩
                3)))
            C = WorksheetFunction.CountIf(Range(Cells(5 + 1, 3), Cells(5 + NrMus, 3)), Cells(5 + j, 3)↩
                .Value)
            A = WorksheetFunction.Average(r, r + C - 1)
            A = NrMus + 1 - A
            'Write the rank to column 5 i the SPRC_diff sheet
            Cells(5 + j, 6).Value = A
        End If
    Next j
    'Calculate the mean objective rank
    Cells(NrMus + 6, 6).Value = WorksheetFunction.Average(Range(Cells(6, 6), Cells(5 + NrMus, 6)))
    Cells(NrMus + 7, 6).Value = WorksheetFunction.StDev(Range(Cells(6, 6), Cells(5 + NrMus, 6)))
    'CALCULATE THE DIFFERENCE d BETWEEN THE TWO RANKS and the d^2
    For j = 1 To NrMus
        If IsNumeric(Cells(5 + j, 2).Value) And IsNumeric(Cells(5 + j, 3).Value) Then
            Cells(5 + j, 8).Value = Cells(5 + j, 5) - Cells(5 + j, 6)
            Cells(5 + j, 9).Value = Cells(5 + j, 8).Value ^ 2
        End If
    Next j
    'CALCULATE THE SUM OF ALL THE DIFFERENCES SQUARE
    Cells(6, 15).Select
    ActiveCell.Value = WorksheetFunction.Sum(Range(Cells(5 + 1, 9), Cells(5 + NrMus, 9)))
    'CALCULATE THE DIFFERENCE BETWEEN RANKS AND THE MEAN OF RANK FOR X and Y
    'CALCULATE THE PRODUCT OF THE DIFFERENCES
    For j = 1 To NrMus
        If IsNumeric(Cells(5 + j, 2).Value) And IsNumeric(Cells(5 + j, 3).Value) Then
            Cells(5 + j, 11).Value = Cells(5 + j, 5).Value - Cells(NrMus + 6, 5).Value
            Cells(5 + j, 12).Value = Cells(5 + j, 6).Value - Cells(NrMus + 6, 6).Value
            Cells(5 + j, 13).Value = Cells(5 + j, 11).Value * Cells(5 + j, 12).Value
        End If
    Next j
    'CALCULATE THE SUM OF THE PRODUCT OF THE DIFFERENCES
    Cells(NrMus + 6, 13).Value = WorksheetFunction.Sum(Range(Cells(6, 13), Cells(5 + NrMus, 13)))
    'CALCULATE THE COVARIENCE BY DIVIDING THE SUM OF THE PRODUCT OF THE DIFFERENCES BY NrMus - 1
    Cells(NrMus + 7, 13).Value = Cells(NrMus + 6, 13).Value / (Cells(5, 15).Value - 1)
    'CALCULATE THE CORRELATION COEFFICIENT r
    'Cells(7, 15).Value = 1 - ((6 * Cells(6, 15).Value) / (Cells(5, 15).Value * (Cells(5, 15).Value ^ ↩
        2 - 1)))
    If (Cells(NrMus + 7, 5).Value * Cells(NrMus + 7, 6).Value) <> 0 Then
        Cells(7, 15).Value = Cells(NrMus + 7, 13).Value / (Cells(NrMus + 7, 5).Value * Cells(NrMus + ↩
            7, 6).Value)
    Else
        Cells(7, 15).Value = "N/A"
    End If
    Application.ScreenUpdating = True
    Application.DisplayAlerts = True
    End Sub
```

F Appendix

Identification of outliers

```
Sub Outliers()

'
'*************************************************************************************
'       Function    Check for outliers in the data
'
'*************************************************************************************
'
'
Application.ScreenUpdating = False
Application.DisplayAlerts = False
'OUTSIDE LOOP go through all subjective parameters OAI,SUP, DYN, ENS, SPL, COL, HS, and REV
    'Check how many musicians have participated in the survey
    Dim NrMus As Integer
    NrMus = 0
    'Count how many musicians participated in the the hall
    Cells(1, 3).Select
    If IsEmpty(ActiveCell) = False Then
        Do
            NrMus = NrMus + 1
            'move down
            ActiveCell.Offset(0, 1).Select
        Loop Until IsEmpty(ActiveCell) = True
    Else
        'Do nothing
    End If
    'COPY the data to 50 cells below
    Range(Cells(7, 3), Cells(14, NrMus + 2)).Select
    Selection.Copy
    Cells(50, 3).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=False, Transpose:=↩
        False
    'Define upper limit and lower limit column number
    Dim UL_col As Integer, LL_col As Integer
    'look for "lower limit" in row and find the column number
    LL_col = Rows(1).Find("lower limit", Cells(1, 1), xlValues, xlWhole, xlByRows, xlNext).Column
    UL_col = LL_col + 1
    'Loop over the subjective parameters in the rows
    For j = 50 To 57
        'Loop over the amount of musicians
        For jj = 3 To NrMus + 2
            'If value is less than lower limit or more than upper limit
            If IsNumeric(Cells(j, jj).Value) Then
                If Cells(j, jj).Value < Cells(j - 50 + 7, LL_col) Or Cells(j, jj).Value > Cells(j ↩
                    - 50 + 7, UL_col) Then
                    'Copy the outlier num-data
                    Cells(j + 10, jj).Select
                    ActiveCell.Value = Cells(j, jj).Value
                    'Add _o in cell
                    Cells(j, jj).Select
                    ActiveCell.Value = Cells(j, jj).Value & "_o"
                Else
                    'Let it be
                End If
            End If
        Next jj
    Next j
    Application.ScreenUpdating = True
    Application.DisplayAlerts = True
End Sub
```

G Appendix

Import from CATT to Excel

```
Sub CATT2Excel()
'
'*********************************************************************************
'       Function     Imports the data from CATT txt-files and pastes that data into a
'                    spreadsheet with corresponding name.
'
'*********************************************************************************
'
'CREATE LOOP THAT WILL GO THROUGH ALL THE DIFFERENT ROOMS IN THE OVERVIEW SHEET
    Application.ScreenUpdating = False
'FIND PROJECT NAMES AND ROWS
    Sheets("Overview").Activate
    Dim ProjectName(1 To 200) As String, ProjectRow(1 To 200) As Integer
    Dim pp As Integer
    pp = 0
    Cells(1, 1).Select
    For iii = 1 To 200
        ActiveCell.Offset(1, 0).Select
        If ActiveCell = Empty Then
            'do nothing
        Else
            pp = pp + 1
            ProjectName(pp) = ActiveCell.Value
            ProjectRow(pp) = ActiveCell.Row
        End If
    Next iii
'LOOP THE PROJECT STRUCTURE
    For ii = 1 To pp
        Sheets("Overview").Activate
        Dim p As Integer
        p = 0
        Cells(ProjectRow(ii) + 2, 3).Select
        'Find how many Folders or models there are
        If IsEmpty(ActiveCell) = False Then
            Do
                p = p + 1
                'move down
                ActiveCell.Offset(0, 4).Select
            Loop Until IsEmpty(ActiveCell) = True
        Else
        'Do nothing
        End If
' LOOP THE FOLDER STRUCTURE
        For i = 1 To p
            ' How much the model is spaced to the right
            Dim Space As Integer
            Space = 3 + 4 * (i - 1)
            ' Define a counter for the do until loop
            Dim n As Integer, varFolderName As String
            n = 0
            Cells(ProjectRow(ii) + 3 + n, Space - 1).Select
            'Find how many sources/subfolders
            If IsEmpty(ActiveCell) = False Then
                Do
                    'delete value in cell
                    Selection.Clear
                    'move down
                    ActiveCell.Offset(1, 0).Select
                Loop Until IsEmpty(ActiveCell) = True
            Else
            'Do nothing
            End If
            ' when looping over i get the folder name
            varFolderName = Sheets("Overview").Cells(ProjectRow(ii) + 1 + n, Space).Value
        'CREATE ALL EXCELSHEETS WITH CORRECT NAMES
            Do
                ' Define the VersionName,
                Dim varVersionName As String, varNrRooms As Integer, CATTsrc As String
                varVersionName = Sheets("Overview").Cells(ProjectRow(ii) + 3 + n, Space).Value
                CATTsrc = Sheets("Overview").Cells(ProjectRow(ii) + 3 + n, Space + 1).Value
                'Write number of source next to name of subfolder
                varNrRooms = n + 1
                Sheets("Overview").Cells(ProjectRow(ii) + 3 + n, Space - 1).Value = varNrRooms
                ' delete sheet if it exists Alerts are turned off and back on
```

```
                On Error Resume Next
                    Sheets(ProjectName(ii) & "_" & varFolderName & "_" & varVersionName).Delete
                On Error GoTo 0
                ' Add new sheet
                Sheets.Add.Name = ProjectName(ii) & "_" & varFolderName & "_" & varVersionName
    'IMPORT THE CORRECT TXT-FILE TO THE CORRECT WORKSHEET
                ' Define string that holds filename
                Dim fName As String
                ' Define the filename path
                fName = ThisWorkbook.Path & "\..\" & "CATT\" & ProjectName(ii) & "\" & ↩
                    varFolderName & "\" & varVersionName & "\" & "OUT" & "\" & "PARAM_" & CATTsrc↩
                     & "x.TXT"
                Sheets(ProjectName(ii) & "_" & varFolderName & "_" & varVersionName).Activate
                ' This code converts the textfile into Excel-tables from recorded Makro
                Range("A1").Activate
                With ActiveSheet.QueryTables.Add(Connection:= _
                    "TEXT;" & fName _
                    , Destination:=Range("A1"))
                    .Name = varVersionName
                    .FieldNames = True
                    .RowNumbers = False
                    .FillAdjacentFormulas = False
                    .PreserveFormatting = True
                    .RefreshOnFileOpen = False
                    .RefreshStyle = xlInsertDeleteCells
                    .SavePassword = False
                    .SaveData = True
                    .AdjustColumnWidth = True
                    .RefreshPeriod = 0
                    .TextFilePromptOnRefresh = False
                    .TextFilePlatform = 850
                    .TextFileStartRow = 1
                    .TextFileParseType = xlDelimited
                    .TextFileTextQualifier = xlTextQualifierDoubleQuote
                    .TextFileConsecutiveDelimiter = False
                    .TextFileTabDelimiter = True
                    .TextFileSemicolonDelimiter = True
                    .TextFileCommaDelimiter = False
                    .TextFileSpaceDelimiter = False
                    .TextFileColumnDataTypes = Array(1)
                    .TextFileTrailingMinusNumbers = True
                    .Refresh BackgroundQuery:=False
                End With
                'Go back to Overview for comfort of user
                Sheets("Overview").Activate
                Cells(ProjectRow(ii) + 3 + n, Space).Select
                ' Add 1 to n in order to increase the amount of sources
                n = n + 1
            Loop Until IsEmpty(ActiveCell.Offset(1, 0)) = True
        Next
        'Say that files have been imported
    Next

    Application.ScreenUpdating = True
End Sub
```